



National Acid Precipitation Assessment Program Report to Congress:

An Integrated Assessment



2005

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2005		2. REPORT TYPE		3. DATES COVERED 00-00-2005 to 00-00-2005	
4. TITLE AND SUBTITLE National Acid Precipitation Assessment Program Report to Congress: An Integrated Assessment				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Science and Technology Council, Executive Office of the President, 725 17th Street Room 5228, Washington, DC, 20502				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 98	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

This document contains links leaving the EPA.gov domain. These links provide additional information that may be useful or interesting and are being provided consistent with the intended purpose of the EPA Web site. However, EPA cannot attest to the accuracy of information provided by these links or any other linked site. Providing links to a non-EPA Web site does not constitute an endorsement by EPA or any of its employees of the sponsors of these sites or the information or products presented on these sites. Also, be aware that the privacy protection provided on the EPA.gov domain (see Privacy and Security Notice) may not be available at these external links.

EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

Members of Congress:

I am pleased to transmit the *National Acid Precipitation Assessment Program Report to Congress: An Integrated Assessment*. This report presents the latest scientific information and analysis concerning the costs, benefits, and environmental effectiveness of the Acid Rain Program. This Program was mandated by Title IV of the 1990 Clean Air Act Amendments to reduce sulfur dioxide (SO₂) and nitrogen oxides (NO_x) emissions from electric generating sources. The SO₂ program includes the use of an innovative emissions cap and trade program. Title IX of the 1990 Clean Air Act Amendments requires the National Acid Precipitation Assessment Program (NAPAP) to report to Congress the costs, benefits, and effectiveness of the Acid Rain Program and characterize what deposition reductions would be necessary to prevent adverse ecological effects in acid sensitive ecosystems. This report fulfills the requirements of Title IX.

NAPAP coordinates federal acid rain research and monitoring under the auspices of the National Science and Technology Council (NSTC) Committee on Environment and Natural Resources (CENR). The NAPAP member agencies are the U.S. Environmental Protection Agency, the U.S. Department of Energy, the U.S. Department of Interior/U.S. Geological Survey, the U.S. Department of Interior/National Park Service, the National Aeronautics and Space Administration, and the National Oceanic and Atmospheric Administration. This assessment involved many individuals from across the federal agencies representing numerous scientific disciplines. NAPAP sought review from several academic perspectives as well, and the results reported here were subjected to extensive peer review.

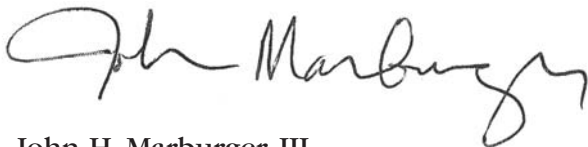
The NAPAP Report analyzes the results of the Acid Rain Program through 2002. The report uses quantitative and qualitative indicators to assess the effectiveness of the cap and trade approach to reduce emissions, improve air quality and reduce acid deposition while minimizing compliance costs. It closely tracks emission reductions since implementation of Title IV in 1995 and includes analysis of emission reductions, compliance, the operation of the sulfur dioxide (SO₂) allowance market and program costs. The report also identifies emerging areas of acid rain research, long-term environmental monitoring and assessment and urges continued support for integrated assessments.

The report also contains the status and trends of emission reductions in SO₂ and NO_x and associated environmental impacts. The report concludes that Title IV has been successful in improving air quality, visibility and achieving broad-scale reductions in sulfate deposition. During Phase I of the program, SO₂ emissions from power plants were 25–40% below

allowable levels, resulting in larger human health and environmental benefits during those years. Such emissions will continue to decline to approximately 9.86 million tons in 2010. While there have not been similar broad-scale reductions in nitrogen deposition, the report indicates that nitrogen deposition has declined in some areas with resulting benefits. Overall a 40% reduction in NO_x emissions from power plants, compared with 1990 levels, is expected by 2010 through Title IV and the NO_x SIP Call.

As emissions of SO₂ approach the cap level established in Title IV and compliance occurs under Title IV and the NO_x SIP Call, air quality is expected to show continued improvement and there will be some additional reduction in deposition. Some lakes and streams, particularly in the Northeast, are beginning to show signs of recovery from acidification. The report, however, also indicates that emission reductions beyond Title IV alone are not sufficient to allow sensitive forests and aquatic systems to recover. In this regard, the report analyzed three scenarios that included reductions beyond those directly required by Title IV. While the scenarios were able to include emission reductions from the NO_x SIP Call and certain state programs, they did not, however, include other existing Clean Air Act programs, including mobile source reductions.

Since the analysis for this report was concluded, EPA finalized several rules that will result in further substantial reductions of SO₂ and NO_x, including the Clean Air Interstate Rule, the Non-Road Diesel Rule and the Best Available Retrofit Technology guidance for regional haze. States will also reduce SO₂ and NO_x as necessary to attain or maintain the new fine particulate matter and ozone National Ambient Air Quality Standards (NAAQS). As part of ongoing work, NAPAP intends to further analyze the improvements in air quality and the resulting benefits for air quality and the environment.

A handwritten signature in black ink, reading "John H. Marburger, III". The signature is fluid and cursive, with the first name "John" and last name "Marburger" being more prominent, and "H. III" written in smaller script between them.

John H. Marburger, III
Director

Acknowledgements

The NAPAP Office of the Director would like to thank all those who wrote, edited, and reviewed this NAPAP Report to Congress. Special thanks are extended to the extramural peer reviewers, who, in addition to providing a technical review, were asked to consider the relationship of this report to public policy. Their comments and suggestions make this a significantly better report.

Peer Reviewers

Dallas Burtraw, Resources for the Future

Thomas Butler, Cornell University

Kenneth Colburn, Northeast States for Coordinated Air Use Management (NESCAUM)

Charles Driscoll, Syracuse University

David Grigal, University of Minnesota

Primary Authors and Contributors

INTRODUCTION AND EXECUTIVE SUMMARY

Tamara Saltman, U.S. Environmental Protection Agency

CHAPTER 1: PROGRAM ELEMENTS AND IMPLEMENTATION

U.S. Environmental Protection Agency/Clean Air Markets Division

CHAPTER 2: RESULTS OF THE ACID RAIN PROGRAM: STATUS AND TRENDS OF EMISSIONS AND ENVIRONMENTAL IMPACTS (1990–2002)

Robert Cook, U.S. Department of Energy Oak Ridge National Laboratory

Chris Eagar, U.S. Department of Agriculture Forest Service

Mark Fenn, U.S. Department of Agriculture Forest Service

Richard Haeuber, U.S. Environmental Protection Agency

Tom Huntington, U.S. Department of Interior/Geological Survey

Sandy McLaughlin, U.S. Department of Energy Oak Ridge National Laboratory

Peter Murdoch, U.S. Department of Interior/U.S. Geological Survey

Tamara Saltman, U.S. Environmental Protection Agency

David Schmeltz, U.S. Environmental Protection Agency

Mary Striegel, U.S. Department of Interior/National Park Service

Carl Trettin, U.S. Department of Agriculture Forest Service

CHAPTER 3: ASSESSING ACID DEPOSITION: ADVANCES IN THE STATE OF THE SCIENCE

Bryan Bloomer, U.S. Environmental Protection Agency
 Robert Cook, U.S. Department of Energy Oak Ridge National Laboratory
 Chris Eagar, U.S. Department of Agriculture Forest Service
 Mark Fenn, U.S. Department of Agriculture Forest Service
 Richard Haeuber, U.S. Environmental Protection Agency
 Tom Huntington, U.S. Department of Interior/Geological Survey
 Sandy McLaughlin, U.S. Department of Energy Oak Ridge National Laboratory
 Mary Ross, U.S. Environmental Protection Agency
 David Schmeltz, U.S. Environmental Protection Agency
 Mary Striegel, U.S. Department of Interior/National Park Service
 Carl Trettin, U.S. Department of Agriculture Forest Service

CHAPTER 4: EXPECTATIONS FOR FULL IMPLEMENTATION OF TITLE IV IN 2010

Bryan Bloomer, U.S. Environmental Protection Agency
 B.J. Cosby, University of Virginia
 Tamara Saltman, U.S. Environmental Protection Agency
 Ann Watkins, U.S. Environmental Protection Agency

CHAPTER 5: BEYOND TITLE IV: ECOLOGICAL IMPACTS OF FURTHER EMISSION REDUCTIONS

B.J. Cosby, University of Virginia
 Richard Haeuber, U.S. Environmental Protection Agency
 Tamara Saltman, U.S. Environmental Protection Agency

About the National Acid Precipitation Assessment Program

The National Acid Precipitation Assessment Program (NAPAP) is a cooperative federal program first authorized in 1980 to coordinate acid rain research and report the findings to Congress. The research, monitoring, and assessment efforts by NAPAP and others in the 1980s culminated in Title IV of the 1990 Clean Air Act Amendments, also known as the Acid Deposition Control Program. In a bold new approach to environmental protection, Title IV includes a market-based program that provides economic incentives for controlling emissions of sulfur dioxide from electricity generating facilities. Title IX of the CAAA reauthorized NAPAP to conduct acid rain research and monitoring

and to periodically assess the costs, benefits, and effectiveness of Title IV. The NAPAP member agencies are the U.S. Environmental Protection Agency, the U.S. Department of Energy, the U.S. Department of Agriculture, the U.S. Department of Interior, the National Aeronautics and Space Administration, and the National Oceanic and Atmospheric Administration. This report is the third published by NAPAP since 1990 assessing Title IV.

In 1997 NAPAP began to operate under the auspices of the Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council. NAPAP's goal continues to be providing credible technical findings on acid deposition and its effects to inform the public decision-making process. To ensure that this goal is met, NAPAP coordinates its activities through the Air Quality Research Subcommittee of the CENR.

Table of Contents

Executive Summary	1
Long-Term Environmental Monitoring	3
Key Components of a Model Program	3
Introduction	4
NAPAP Mission	4
Structure of the Report	5

Chapter 1. Program Elements and Implementation

Emission Reductions	6
Program Design	6
SO ₂ Program	6
NO _x Program	7
Title IV Affected Sources	8
Compliance	8
SO ₂ Program	8
NO _x Program	9
SO ₂ Allowance Market	10
Program Costs	12
Phase I Costs	13
Phase II Costs	13
Administrative Costs	14
Program Assessment	15
Emissions Monitoring	15
Air Quality, Deposition, and Ecological Monitoring	15

Chapter 2. Results of the Acid Rain Program: Status and Trends of Emissions and Environmental Impacts (1990–2002)

Emissions	17
SO ₂ Emissions	17
NO _x Emissions	17
Geographic Distribution of Emissions from Power Generation	20
Geographic Trends in SO ₂ Emissions	20
Geographic Trends in NO _x Emissions	22
Air Quality, Deposition, and Visibility	23
Air Quality: Sulfur	26
Air Quality: Nitrogen	27
Acid Deposition: Sulfur in Precipitation	28
Acid Deposition: Nitrogen in Precipitation	30
Visibility	36

Ecological Recovery	36
Freshwater Acid-Sensitive Ecosystems	36
Forest Ecosystems	41
Coastal Ecosystems	43
Materials and Structures	43

Chapter 3. Assessing Acid Deposition: Advances in the State of the Science

Air Quality, Deposition, and Visibility	44
Aquatic and Forest Ecosystems	46
Freshwater Acid-Sensitive Ecosystems	46
Forest Ecosystems	48
Coastal Ecosystems	49
Materials and Structures	49
Human Health	51
Modeling	52
Atmospheric Modeling	55
Nonlinear Responses to Decreases in SO ₂ and NO _x Emissions	53
Water/Watershed Modeling	53
Health Effects Modeling	56

Chapter 4. Expectations for Full Implementation of Title IV in 2010

Emissions	58
Acid Deposition	58
Acidification of Freshwater Lakes and Streams	61
Human Health	63
Other Benefits of Title IV	64

Chapter 5. Beyond Title IV: Ecological Impacts of Further Emission Reductions

Analysis of the Environmental Impact of Further Air Emission Reductions	67
Scenarios Analyzed	67
Changes in Acid Deposition	68
Changes in Sulfur Deposition	68
Changes in Nitrogen Deposition	70
Water Quality	70
Summary	73

References	75
------------	----

List of Figures and Tables for NAPAP Report

- Figure 1. Sensitive ecological receptors in the United States
- Figure 2. Title IV affected sources—2002
- Figure 3. Percent of SO₂ emission reductions by compliance option for Acid Rain Program sources—2001
- Figure 4. SO₂ allocations for electric generating units, 1995–2002
- Figure 5. Nominal SO₂ allowance prices, 1994–2002
- Figure 6. SO₂ allowances transferred, 1994–2002
- Figure 7. Estimated costs of implementation of Title IV SO₂ emission reductions in 2010, 1989–1998
- Figure 8. SO₂ emissions from all affected sources (electric generating units), 1980–2002
- Figure 9. SO₂ emissions from all sources, 1980–2001
- Figure 10. NO_x emissions from all affected sources (electric generating units), 1990–2002
- Figure 11. Energy use and NO_x emissions by state, 1990–2002
- Figure 12. NO_x emissions from all sources, 1990–2001
- Figure 13. SO₂ emission trends from power generation facilities by state, 1990–2002
- Figure 14. NO_x emission trends from power generation facilities by state, 1990–2002
- Figure 15. Location of NADP/NTN, CASTNET, and IMPROVE monitoring sites and pollutants measured by major networks
- Figure 16. Comparison of annual ambient sulfur dioxide (SO₂) concentrations in the rural Eastern United States from CASTNET monitoring data, 1989–1991 vs. 2000–2002
- Figure 17. Comparison of annual ambient sulfate (SO₄²⁻) concentrations in the rural Eastern United States
- Figure 18. Comparison of annual ambient nitric acid (HNO₃) concentrations in the rural Eastern United States
- Figure 19. Comparison of annual ambient nitrate (NO₃⁻) concentrations in rural Eastern United States
- Figure 20. Comparison of annual ambient ammonium (NH₄⁺) concentrations in rural Eastern United States
- Figure 21. Comparison of annual wet sulfate (SO₄²⁻) deposition in the United States
- Figure 22. Comparison of annual total (wet plus dry) sulfur deposition in the United States
- Figure 23. Comparison of annual wet nitrate (NO₃⁻) deposition in the United States
- Figure 24. Comparison of annual concentrations of nitrate (NO₃⁻) in wet deposition in the United States
- Figure 25. Comparison of annual total (wet plus dry) nitrogen deposition in the United States
- Figure 26. Trends in visibility in Class 1 areas, 1992–2001
- Figure 27. Relationship between acid neutralizing capacity (ANC) and the number of species present in aquatic freshwater ecosystems in Shenandoah National Park
- Figure 28. Map of the Temporally Integrated Monitoring of Ecosystems (TIME) monitoring network

- Figure 29. Trend in acidification of eastern lakes and streams, 1990–2000
- Figure 30. Projected change in wet sulfate deposition in 2010 with Title IV compared to conditions in 1989–1991 and 2000–2002
- Figure 31. Projected change in inorganic wet nitrogen deposition in 2010 with Title IV compared to conditions in 1989–1991 and 2000–2002
- Figure 32. Projected change in the number of chronically acidic lakes and streams in 2030 with and without Title IV
- Figure 33. Stages of recovery for acidic lakes and streams
- Figure 34. Projected percent change in annual sulfur deposition from base case in 2020 with additional SO₂ and NO_x emission reductions
- Figure 35. Projected percent change in annual nitrogen deposition from base case in 2020 with additional SO₂ and NO_x emission reductions
- Figure 36. Change in the number of chronically acidic lakes and streams in 2030 with additional SO₂ and NO_x emission reductions

TABLES

- Table 1. Nitrogen contribution to estuaries in the United States from atmospheric deposition (direct and indirect)

Executive Summary

Acid deposition, more commonly known as acid rain, occurs when emissions of sulfur dioxide (SO₂) and nitrogen oxides (NO_x) react in the atmosphere (with water, oxygen, and oxidants) to form various acidic compounds. These acidic compounds then fall to earth in either a wet form (rain, snow, and fog) or a dry form (gases, aerosols, and particles). Prevailing winds transport the acidic compounds hundreds of miles, often across state and national borders. At certain levels the acidic compounds, including small particles such as sulfates and nitrates can cause many negative human health and environmental effects. While ecosystems are subject to many stresses, including land-use changes, climate change, and variations in hydrologic and meteorologic cycles, the scientific literature has clearly demonstrated that these pollutants can:

- Degrade air quality,
- Impair visibility,
- Damage public health,
- Acidify lakes and streams,
- Harm sensitive forests,
- Harm sensitive coastal ecosystems, and
- Accelerate the decay of building materials, paints, and cultural artifacts such as buildings, statues, and sculptures.

Title IV was passed by Congress as part of the 1990 Clean Air Act Amendments to reduce emissions of SO₂ and NO_x from fossil fuel-burning power plants in order to protect ecosystems suffering damage from acid deposition and to improve air quality. At the same time, the National Acid Precipitation Assessment Program (NAPAP) was asked to periodically assess and report to Congress on the implementation of the Acid Rain Program, recent scientific knowledge surrounding acid deposition and its effects, and the reduction in acid deposition necessary to prevent adverse ecological effects. This NAPAP Report focuses primarily on emission reductions from power plants, both in terms of assessing past reductions under the Acid Rain Program and in projecting the ecological effects of additional reductions of SO₂ and NO_x.

It should be noted that power generation currently contributes approximately 69% of the SO₂ emissions and 22% of the NO_x emissions nationwide. This contribution is decreasing as emissions from power generation continue to decrease, making the other sources of these pollutants more prominent. Modeling suggests that even if SO₂ emissions from power generation were reduced to zero, some lakes and streams would remain acidic due to acid deposition. However, there are several other regulations that reduce emissions of SO₂ and NO_x from these non-power generation sources, such as the Tier II mobile source standards, the Heavy Duty Diesel standards, and the Clean Air Non-Road Diesel Rule, that have also been promulgated since 1990. These regulations, primarily designed to bring counties into attainment with fine particle and ozone air quality standards, also incidentally reduce emissions that contribute to acid deposition.

Implementation of Title IV has successfully and substantially reduced emissions of SO₂ and NO_x from power generation at a significantly lower cost than expected:

- In 2002, SO₂ emissions were 10.2 million tons, 35% lower than 1990 emissions and 40% lower than 1980 emissions.*
- In 2002, NO_x emissions were 4.5 million tons, 33% lower than 1990 emissions.

In addition, SO₂ emissions from all sources have decreased by 32% since 1990 and emissions of NO_x from all sources have decreased by 12% since 1990. Power generating sources continue to close in on the goal of reducing power plant SO₂ emissions from 1980 levels by 50% (to 8.95 million tons) as required by the 1990 Clean Air Act. Power generating sources have also exceeded-

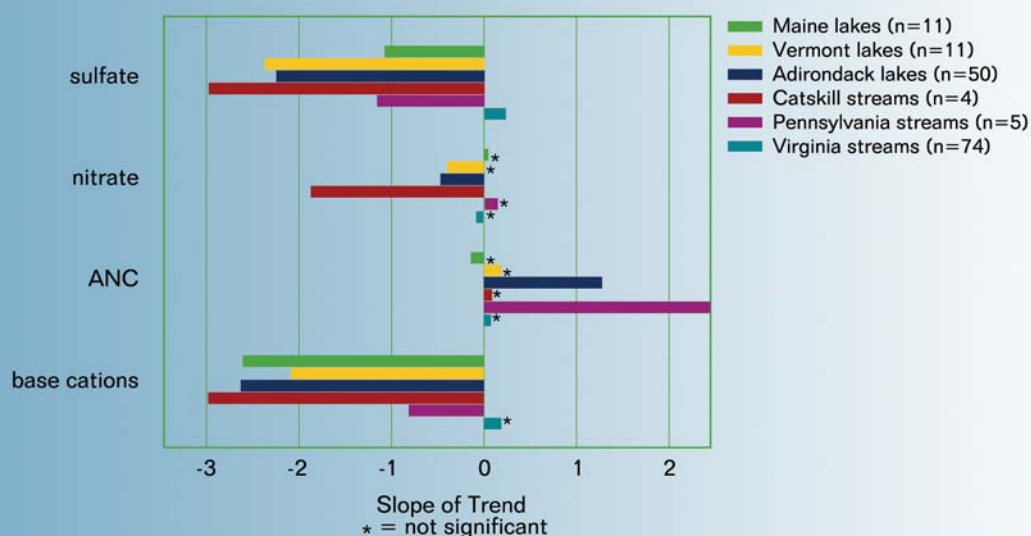
* 2002 was the latest year for which emissions data were available when this report was written and reviewed. More recent emissions data are available on the EPA Web site at www.epa.gov/airmarkets/emissions.

ed the goal of a two million ton reduction in NO_x emissions from projected 2000 levels as required by the 1990 Clean Air Act.

These emission reductions have contributed to measurable improvements in air quality, reductions in acid deposition, and the beginnings of recovery of acid-sensitive waters in some areas:

- SO₂ concentrations in the atmosphere (a precursor to fine particles and acid deposition) have decreased since 1990. Average annual SO₂ concentrations in the Northeast in 2000–2002 were 40% lower than they were in 1989–1991, concentrations in the mid-Atlantic were 30% lower, concentrations in the Southeast were 35% lower, and concentrations in the Midwest were 45% lower.
- Sulfate concentrations in the atmosphere (a major component of fine particles, especially in the East) have decreased since 1990 as well. Average annual sulfate concentrations in the Northeast and Midwest in 2000–2002
- were approximately 30% lower than they were in 1989–1991, and concentrations in the mid-Atlantic and Southeast were 25% lower.
- Wet sulfate deposition, a major component of acid rain, has also decreased since 1990. Average annual sulfate deposition in the Northeast in 2000–2002 was 40% lower than it was in 1989–1991, deposition in the mid-Atlantic and Midwest was 35% lower, and deposition in the Southeast was 25% lower.
- Wet nitrate deposition has not decreased regionally from historical levels because of the relatively moderate NO_x reduction from power plants and the continuing large contribution (over 50% of total NO_x emissions) from other sources of NO_x such as vehicles and nonroad vehicles.
- Although visibility has begun to improve in some parts of the U.S., there is still significant impairment of visibility in many national parks and other Class I areas throughout the U.S.
- Acid neutralizing capacity is beginning to rise in some surface waters in the Northeast, including lakes in the Adirondack Mountains (see graphic below). This is an indication that recovery from acidification is occurring in those areas.

Trend in acidification of eastern lakes and streams 1990–2000



Note: Decreasing values for sulfate and nitrate indicate reductions in acidity; increasing values for ANC indicate recovery of the capacity to buffer acid deposition without becoming acidic. Decreasing values for base cations can balance out decreasing sulfate and nitrate values, preventing ANC from increasing and leaving waters vulnerable to acidification.

Source: Stoddard et al., 2003. Response of surface water chemistry to the Clean Air Act Amendments of 1990 (See #36 in References section.)

- Reductions in fine particles due to reductions in emissions of SO₂ and NO_x are expected to continue to benefit human health by substantially lowering the incidence of respiratory and cardiovascular illnesses.

Sources in both the more conventional emission rate-based NO_x program and the cap and trade program for SO₂ have demonstrated a high level of compliance, and their efforts have achieved measurable environmental results. The flexibility for sources to choose how to control their emissions inherent in the cap and trade approach for SO₂ has been successful at reducing compliance costs to a fraction of the cost estimated in 1990. It has not resulted in any significant geographic shifts in SO₂ emissions. The annual cost of the SO₂ trading program by 2010 is expected to be approximately \$1 to \$2 billion per year (\$2000), far lower than the estimated \$6 billion annual cost in 1990 (\$2000).

Emissions of SO₂ are expected to continue to decline as the bank of allowances that was built up in Phase I of the Acid Rain Program (as a result of reductions beyond those required) is largely depleted. At that point, annual emissions will approximate annual allocations of emission allowances. Thus, annual emissions will equal 8.95 million tons (the level of the cap). Air quality, visibility, and ecosystems are expected to continue to improve as emissions decrease, and deposition is also expected to continue to decrease. A recent estimate of the health benefits of Title IV in 2010 indicates that the benefits are substantial, including thousands fewer premature deaths and hospital admissions and emergency room visits.

Despite anticipated environmental improvements, research over the last few years indicates that recovery from the effects of acidification is not possible for many areas that continue to be exposed to acid deposition. Many published articles, as well as the modeling presented in this report, show that the SO₂ and NO_x emission reductions achieved under Title IV from power plants are now recognized as insufficient to achieve recovery or to prevent further acidification in some regions. Additional SO₂ and NO_x emission reductions from power plants and other source sectors are needed to improve air quality, reduce deposition, and further reduce the number of acidic lakes and streams in many regions of the U.S. Some of these additional emission reductions may be achieved through implementation of existing or future regulations to address transport of ozone and fine particles and mercury deposition, including the NO_x SIP call in the Eastern U.S., tier II and diesel rules affecting mobile sources, state implementation plans to achieve the ozone and fine particle National Ambient Air Quality Standards, and the recent rules to reduce interstate transport of fine particles and ozone and mercury from power plants.

Long-Term Environmental Monitoring

Emissions, air quality, deposition, and ecological monitoring are critical components of Title IV. These monitoring efforts allow researchers and policymakers to assess the effectiveness of the Title IV program. Emissions monitoring is conducted by affected sources; the other types of monitoring are conducted by a wide variety of federal and state agencies, universities, and other organizations. The agencies of the National Acid Precipitation Assessment Program (NAPAP) continue to have a strong commitment to the research and monitoring that makes assessments like this NAPAP Report to Congress possible.

Key Components of a Model Program

Title IV serves as a model structure of an air pollution control program because of its significant and measurable progress towards meeting its emission reduction goals and the low costs associated with its implementation. The program's guiding principles of the cap on emissions, complete accountability, and simplicity are largely responsible for its effectiveness. The cap is the core prerequisite of an effective and efficient trading program that guarantees the environmental goals are achieved and sustained. Accountability, including reliable emissions, air quality, atmospheric deposition, and ecological monitoring and regular assessment of progress towards the goals, promotes both public confidence in the environmental integrity of the program and business confidence in the financial integrity of the allowance market. The simple, clear, straightforward nature of Title IV has resulted in high levels of compliance, low administrative costs, and timely achievement of its environmental goals.

Introduction

NAPAP Mission

The National Acid Precipitation Assessment Program (NAPAP) is comprised of the U.S. Environmental Protection Agency, the U.S. Department of Energy, the U.S. Department of Interior/U.S. Geological Survey, the U.S. Department of Interior/National Park Service, and the National Oceanic and Atmospheric Administration. Under Title IX of the 1990 Clean Air Act Amendments, Congress reauthorized NAPAP to continue coordinating acid rain research and monitoring, as it had done during the previous decade, and to provide Congress with periodic reports. In particular, Congress asked NAPAP to assess all available data and information to answer two questions:

- What are the costs, benefits, and effectiveness of Title IV? This question addresses the costs and economic impacts of complying with the Acid Rain Program as well as benefit analyses associated with the various human health and welfare effects, including reduced visibility, damages to materials and cultural resources, and effects on ecosystems.
- What reductions in deposition rates are needed to prevent adverse ecological effects? This complex question addresses ecological systems and the deposition levels at which they experience harmful effects.

The results of the assessment of the effects of Title IV and of the relationship between acid deposition rates and ecological effects were to be reported to Congress quadrennially, beginning with the 1996 report to Congress. The objective of this Report is to address the two main questions posed by Congress and fully communicate the results of the assessment to decision-makers. Given the primary audience, most of this report is not written as a technical document,

although information supporting the conclusions is provided along with references.

Impacts of SO₂ and NO_x Emissions

Title IV of the 1990 Clean Air Act Amendments (CAAA) requires significant reductions of sulfur dioxide (SO₂) and nitrogen oxide (NO_x) emissions. These emissions contribute to acid deposition, ultimately leading to a wide range of environmental impacts, as well as the formation of fine particles and gases that can harm health and impair visibility. Some places and people are more susceptible or sensitive to the impacts of SO₂ and NO_x emissions than others. Some people (especially children, the elderly, and those with existing respiratory or cardiovascular conditions) are more likely to be harmed by fine particles formed from SO₂ and NO_x emissions and ozone formed from NO_x emissions.

Areas where acid deposition damages ecosystems or where gases and particles impair visibility are called “sensitive ecological receptors.” Sensitive ecological receptors include lakes and streams throughout the Appalachian Mountains; forests in the Appalachian Mountains, the Colorado Front Range, and western coastal mountain ranges; and many east and gulf coast estuaries and coastal waters (see Figure 1). Many national parks and wilderness areas, including Shenandoah National Park, Great Smoky Mountains National Park, Acadia National Park, and Grand Canyon National Park have impaired visibility due in part to emissions of SO₂ and NO_x from power generation sources. Adirondack Park has a large number of lakes that have been damaged by acidic deposition.

Many of these health and environmental impacts can occur hundreds of miles from where the pollutants are emitted. This long-range transport makes it critical to reduce emissions that contribute to acid deposition and other environmental impacts, even those that occur far from sensitive waters, forests or population centers. The purpose of Title IV is to reduce the ecological impacts of acid deposition by reducing emissions of SO₂ and NO_x from power generation sources. These emission reductions have and will continue to benefit the nation by:

- Improving air quality and protecting public health
- Restoring acidified lakes and streams so they can once again support fish and other aquatic life

FIGURE 1. Sensitive ecological receptors in the United States



Source: EPA

- Improving visibility, especially at scenic vistas in national parks
- Reducing the damage to sensitive forests, such as those along the Appalachian Mountains and in the Colorado Front Range
- Reducing the damage to nitrogen-sensitive coastal waters along the east and gulf coasts
- Protecting our historic buildings and monuments from degradation

Structure of the Report

This report is directed to Congress but provides valuable economic and scientific information to all public officials who are responsible for determining or evaluating air quality policy. Its goal is to present highly technical information pertinent to current public policy issues in a format that can be understood by the nonscientific reader. Where more scientific or economic detail is desired, references are noted in the text with superscripts and provided at the end of the report.

The status of implementation of Title IV by EPA and the affected utilities at the end of 2002 is presented in the first chapter. This is followed by an analysis of the observed

changes, both past and present, in emissions of acid rain precursors, air pollutant concentrations, deposition of acidic species, and various ecological endpoints, particularly surface water quality, in the second chapter. The third chapter covers advances in the state of the science regarding atmospheric deposition monitoring, the impacts of acid deposition on aquatic and terrestrial ecosystems, visibility, materials and cultural resources, and human health. The fourth chapter presents estimates of the changes in air quality, deposition, freshwater acidification, and the human health benefits of full implementation of Title IV in 2010. The fifth chapter addresses the question posed by Congress in the 1990 CAAA regarding the ecological impacts of further emission reductions and the uncertainties in the estimated relationships between emission reductions and the resulting ecological effects.



Chapter 1: Program Elements and Implementation

Title IV has been successfully implemented according to the rules and guidance established by the Acid Rain Program. Emissions have decreased significantly since 1990, and source compliance has been extremely high since the program began. The market-based system for reducing SO₂ emissions is functioning well; there is a significant amount of market activity and SO₂ allowance prices, which have varied from \$65–\$210 per ton, are significantly lower than had been predicted in 1990.

Emission Reductions

Title IV has successfully reduced emissions of SO₂ and NO_x from power generation sources. In 2002, there were approximately 3,200 electric power units subject to the SO₂ provisions of Title IV.* By 2002, these sources had reduced their combined SO₂ emissions by approximately 40% from 1980 levels and 35% from 1990 levels. Although not all sources in the SO₂ trading program are also covered by the NO_x program, the sources in the SO₂ program reduced their NO_x emissions by 33%. The approximately 1,000 sources affected by Title IV NO_x requirements reduced their NO_x emissions by approximately 27% from 1990 levels in 2002. The emission reductions achieved under Title IV are discussed in more detail in Chapter 2.

Program Design

SO₂ PROGRAM

The SO₂ component of Title IV represents a dramatic departure from traditional command and control regulatory approaches that establish source-specific emission limitations. Instead, the program uses an overall emissions cap for SO₂ that ensures emission reductions are achieved and maintained as well as a trading system that facilitates lowest-cost emission reductions. The program features tradable SO₂ emission allowances, where one allowance is a limited authorization to emit one ton of SO₂. A fixed number of allowances are issued by the government, and they may be bought, sold, or banked for future use by utilities, brokers, or anyone else interested in holding them. Existing units are allocated allowances for each year; new units do not receive allowances and instead must buy them. Recent research on the dynamics of the SO₂ allowance market indicates that this is not a substantial barrier to entry; i.e., new sources have had no trouble acquiring the allowances they need to compete effectively in the market.¹ At the end of the year, all affected sources are obliged to surrender to the EPA the number of allowances that correspond to their annual SO₂ emissions (one allowance for each ton of SO₂).

Title IV requires a two-phased tightening of allowances (or SO₂ emission allocations) to fossil fuel-fired power plants in order to reach the permanent cap on the number of allowances at 8.95 million tons annually. Once the bank of unused allowances is depleted, the cap on allocations limits emissions to the level of the cap (8.95 million tons). This permanent cap is approximately half the amount of SO₂ emitted by these power plants in 1980. Phase I of the SO₂ program (1995–1999) affected 263 of the larger (>100 megawatt (MW)), higher emitting units which are located primarily in the Eastern United States. Phase I SO₂ allowance allocations were distributed to each source based on the following formula: the product of an emission rate of 2.5 lb SO₂/million British thermal units (mm BTU) of heat input and its average heat input for 1985–1987. Some Phase II sources chose to “opt-in” to Phase I and comply early, bringing the total number of units in Phase I to over 400.** Phase II began in 2000 and extends to all existing

* These units, as well as an additional 273 units which were retired or not yet operating, are listed in Appendix A of the annual Acid Rain Program Progress Report available at www.epa.gov/airmarkets/cmprpt.

**The number of sources in Phase 1 varied slightly by year due to changes in the number of substitution, compensating, and opt-in units in any given year. These units, which were not identified in the 1990 Clean Air Act as Phase I sources, entered the SO₂ or NO_x programs early in order to reduce costs or take advantage of the SO₂ allowance market.



electric utility units serving generators larger than 25 MW and all new fossil fuel-fired generation units throughout the country. This has brought the total number of units covered by the SO₂ program to approximately 3,200 sources (see Figure 2). In Phase II, all Phase I and Phase II SO₂ affected sources are allocated allowances equivalent to an amount no greater than the product of 1.2 lb SO₂/mm BTU and their average heat input for 1985–1987.

Affected sources must demonstrate compliance with the SO₂ provisions of Title IV at the end of each year. Sources are granted a 60-day grace period during which additional SO₂ allowances may be purchased, if necessary, to cover each unit's emissions for the year. At the end of the grace period (the Allowance Transfer Deadline), the allowances a unit holds in its Allowance Tracking System (ATS) account must equal or exceed the unit's annual SO₂ emissions for the previous year. Title IV requires affected sources to monitor emissions continuously and to report their emissions quarterly. Failure to surrender sufficient allowances results in two significant automatic penalties: a fine and a reduction in the number of allowances allocated in the following year. Any remaining SO₂ allowances not needed for compliance may be sold or banked for future use. Sources may use their banked allowances as needed to comply with the program in future years until the bank is depleted.

NO_x PROGRAM

There are no tradable emission allowances in the NO_x reduction portion of the Acid Rain Program. Instead, sources control how much NO_x is emitted from coal-fired boilers based on the use of cost-effective control technologies for each unit of fuel consumed (lb NO_x/mm BTU). There were also two phases to the NO_x control program: Phase I began in 1996 (delayed one year because of litigation) and Phase II in 2000. During Phase I, which applied to specific coal-fired boilers statutorily affected by Phase I SO₂ requirements, the NO_x emissions rate was set at 0.50 lbs/mm BTU for dry bottom wall-fired units and 0.45 lbs/mm BTU for tangentially-fired units. Beginning in 2000, Phase II plants were required to meet emissions rates between 0.40 lbs/mm BTU and 0.86 lbs/mm BTU depending on the type of boiler.

Although the NO_x program does not include emission trading, sources are provided a degree of flexibility through emission averaging provisions, whereby a company can meet its emission limitations by averaging the

FIGURE 2. Title IV affected sources—2002



Source: EPA

emission rates of two or more boilers. This allows sources to reduce their emissions at lower cost by allowing them to over-control at units where it is technically easier to control emissions. In addition, specific Phase II units elected to comply with Phase I limits beginning in 1997. These “early election units” are not subject to the more stringent Phase II limits until 2008. In 2002 there were over 1,000 units required to meet a NO_x emission limit under Title IV provisions. Since NO_x emission reductions are achieved by limiting the rate of NO_x output per unit of heat input and not through an emission cap, emissions could increase through a combination of increased utilization of existing units and/or construction of new units.

Sources affected by the NO_x portion of Title IV must also demonstrate that they have complied with the NO_x provisions at the end of the year. Sources demonstrate compliance with the NO_x program by achieving an annual emission rate at or below mandated levels as outlined in their EPA-approved compliance plans.

Title IV Affected Sources

Generally, boilers or combustion turbines that burn fossil fuel, serve generators with nameplate capacity greater than 25 MW, and produce electricity for sale are subject to the Title IV SO₂ requirements. There are several types of units, however, that meet these criteria that are not affected by the program:

- **Simple combustion turbines**, regardless of their nameplate capacity, if they began to produce electricity for sale before November 15, 1990.
- **Cogeneration units** whose annual electrical sales remain below the threshold established by regulation (one-third of operating capacity or 219,000 MW per hour, whichever is greater).
- **Specific qualifying facilities** and independent power producers that are contractually bound to sell electricity at a price that was established before November 15, 1990.

Despite these exceptions, almost all non-cogeneration units built in the future that serve generators with total nameplate capacity greater than 25 MW and produce electricity for sale will be affected units that must participate in the Acid Rain Program. Of the units subject to the SO₂ portion of Title IV, some are also covered by the Title IV NO_x Program requirements. All units where coal accounted for more than 50% of its heat input for at least one year during the 1990 through 1995 time period and that are configured for a specific type of boiler (cell burner, cyclone, dry bottom wall-fired, tangentially-fired, vertically-fired, or wet bottom) are affected by the Title IV NO_x Program. For more details on Acid Rain Program applicability criteria, see 40 CFR 72.6, the Acid Rain Program applicability regulations established under Title IV.

Compliance

SO₂ PROGRAM

The Title IV SO₂ program has seen a near-perfect compliance record since the program took effect in 1995. During the compliance process, the number of allowances surrendered at an individual unit must be equal to the number of tons emitted at the unit.* During Phase I (1995–1999) compliance was 100%; in each year since the beginning of Phase II a small number of units (1–6, depending on the year) were short allowances to cover their emissions. For example, in 2002, due to an administrative error on the part of the company, a single unit was short a total of 33 allowances to cover its emissions for the 2002 compliance year. Thirty-three year 2003 allowances were taken from this unit as an “offset.” In addition to the offset, the operator of this unit was assessed an automatic monetary penalty totaling over \$90,000 (\$2002) as prescribed in the Clean Air Act.

The flexibility provided by Title IV enables the sources subject to the Title IV SO₂ program to pursue a variety of compliance options, some of which, such as process innovation, might have been discouraged under other types of control programs.² Sources meet their SO₂ reduction obligations by installing scrubbers, running existing scrubbers more efficiently, switching fuels, changing practices or procedures to improve energy efficiency, and buying allowances. Most sources are complying with the SO₂ requirements in Title IV by blending or switching fuels. In 2001 this accounted for approximately two-thirds of the SO₂ emission reductions (see Figure 3). Scrubbers installed on 30 Phase I units accounted for almost all of the remaining emission reductions in 2001.¹

* The annual deductions for emissions at each unit after the common stack apportionment was made can be found in Appendix A of the most recent annual Acid Rain Program Progress Report available at www.epa.gov/airmarkets/cmprpt. Units sharing a common stack are listed directly under the entry for their common stack.





NO_x PROGRAM

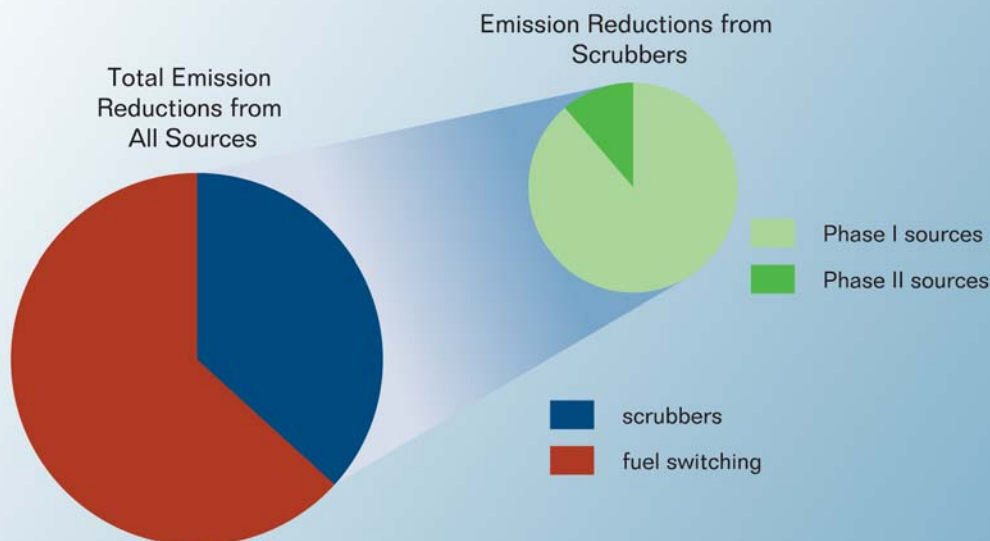
Instead of using allowance trading to facilitate NO_x emission reductions, Title IV establishes limits on NO_x emission rates (in lb NO_x/mm BTU) for coal-fired electric generating units. The various ways a source can meet its emission limit are described below.

- **Standard Limitation.** A unit with a standard limit simply meets the applicable individual NO_x limit prescribed for its boiler (Group 1: dry bottom wall-fired and tangentially-fired boilers; and Group 2: cell burner, cyclone, vertically-fired, and wet bottom boilers) under the Title IV NO_x regulation (40 CFR part 76).
- **Early Election.** Under this compliance option, a Phase II Group 1 NO_x affected unit meets a less stringent Phase I NO_x limit beginning in 1997, three years before it would normally be subject to an Acid Rain NO_x limit. In return for accepting a NO_x limit three years earlier than would normally be required, an early election unit does not become subject to the more stringent Phase II NO_x limit until 2008.
- **Emissions Averaging.** A company can meet its NO_x emissions reduction requirements by choosing to make a group of NO_x program affected boilers subject to a group NO_x limit, rather than meeting individual NO_x limits for

each unit. The group limit is established at the end of each calendar year, and the group rate for the units must be less than or equal to the BTU-weighted rate at which the units would have been limited had each been subject to an individual NO_x limit.

- **Alternative Emission Limitation (AEL).** A utility can petition for a less stringent AEL if it properly installs and operates the NO_x emissions reduction technology prescribed for that boiler but is unable to meet its standard limit. EPA determines whether an AEL is warranted based on analyses of emissions data and information about the NO_x control equipment.

FIGURE 3. Percent of SO₂ emission reductions by compliance option for Acid Rain Program sources—2001



Source: Ellerman, A.D. 2003. Lessons from Phase II compliance with the U.S. Acid Rain Program (See #1 in References section.)

The NO_x program has also had a high rate of compliance. For example, in 2002, 1,047 units met their NO_x emissions limits through compliance with their respective NO_x compliance plans. Only one unit failed to meet its NO_x emissions limit in 2002. That unit had excess NO_x emissions of 47 tons and was assessed a monetary penalty totaling over \$133,000 (\$2002)*. Emissions averaging was the most widely chosen compliance option for NO_x affected units in 2002; more than 50 emission averaging compliance plans involving over 600 units were in place in 2002.

SO₂ Allowance Market

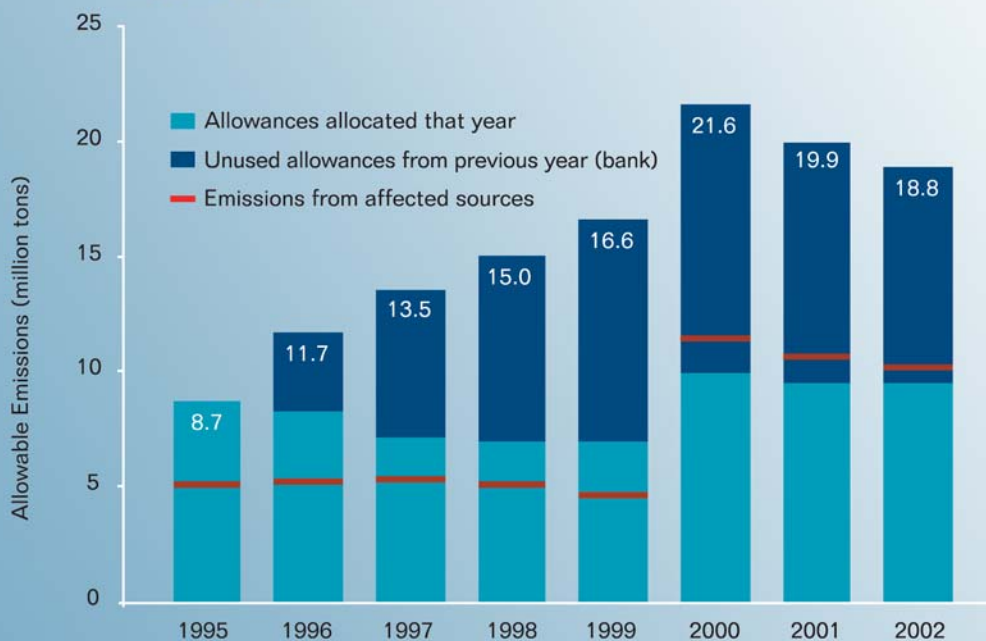
The number of allowances (authorizations to emit SO₂) allocated to each source in any given year is determined by the Clean Air Act. The presence of the allowance market has given some sources the incentive to re-

duce their SO₂ emissions below the level of their allowance allocation in order to sell their allowances to other sources or bank them for use in future years. Other sources have been able to postpone or reduce expenditures for pollution control by purchasing allowances from sources that controlled beyond their allowance allocation level. The SO₂ allowance market is generally thought of as relatively well-functioning due to the “clear, consistent rules that emphasize transparency, fungibility, and market performance [that] have been the key factors in creating the investor certainty...”³

Under Title IV, the “bank” or store of unused allowances grew throughout Phase I (1995–1999) as sources reduced emissions more than required. These “early reductions” reduced the amount of fine particles and acid deposition reaching sensitive ecological receptors in the early years of the acid rain program, increasing the human health and ecological benefits of the program in those years. Beginning in 2000, the tighter emission cap in Phase II took effect, and sources began to use previously banked allowances in addition to allocations from the current year in order to comply with Title IV.



FIGURE 4. SO₂ allocations for electric generating units 1995–2002



Note: From 1995–1999, Title IV covered approximately 400 units; beginning in 2000 the program was extended to approximately 3,200 units.

Source: EPA

* Detailed annual compliance information by unit can be found in Appendices B1 and B2 of the most recent annual Acid Rain Program Progress Report available at www.epa.gov/airmarkets/cmprpt.

FIGURE 5. Nominal SO₂ allowance prices
1994–2002



Note: Allowance prices are reported in nominal year dollars

Source: Cantor Fitzgerald Environmental Brokerage Services

In 2002, a total of 9.5 million allowances were granted to sources as prescribed in Title IV. Adding these 2002 vintage allowances to the unused allowances banked from prior years, a total of 18.8 million allowances were available for use in 2002. Sources emitted 10.2 million tons in 2002, 650,000 tons more than the allowances granted in 2002, but far less than the allowable level. Figure 4 shows the changing size of the allowance bank from 1995 through 2002.

In a well-functioning market, the price of an allowance should equal the expected marginal cost of compliance, the cost of reducing the next ton of SO₂ emitted from the utility sector. Emission reductions continue to cost less than anticipated when Title IV was enacted, and this is reflected in the price of an SO₂ emission allowance. The cost of an allowance was initially estimated at \$250 to \$400/ton during Phase I and at \$500 to \$1,000 for Phase II.⁴ As shown in Figure 5, actual prices have been significantly lower than that. The market price for allowances has tended to fluctuate between \$100 and \$200 per ton and was as low as \$65 in 1996.*

Allowance prices for 2002 continued the downward trend that started in the second half of 2001. Prices hovered in

the \$170/ton dollar range early in 2002 and decreased slightly during the summer months, ending the year in the \$130/ton range. Prices stabilized back to historical averages in 2002 after the more stringent limits in Phase II resulted in higher average prices in 2001. Some market observers believe lower than expected allowance prices during the first several years of the program were due primarily to lower than expected compliance costs (due mostly to increases in the availability of low-sulfur coal) and larger than expected emission reductions, which increased the supply of allowances and put downward pressure on prices.⁵ Market observers believe that technological innovation that resulted in lower than expected costs to operate scrubbers has also contributed to the lower allowance prices.⁶

The level of activity in the allowance market created under Title IV increased fairly steadily through 2000 to over 30 million transfers and then leveled off somewhat in 2001 and

* All allowance prices in this report are reported in current year dollars for the year in which they occurred, unless otherwise indicated.

2002, the second and third years of Phase II (see Figure 6). The number of transfers between economically unrelated organizations—i.e., trades other than those between units or subsidiaries belonging to a single company—also rose fairly steadily from 1994 through 2000 before leveling out in Phase II. In most years, trades between economically unrelated organizations accounted for half or more of all trades.

In 2002, over 5,700 allowance transfers that affected over 21 million allowances (of past, current, and future vintages) were recorded in the Allowance Transfer System, the accounting system developed to track holdings of allowances. Of the allowances transferred, 11.6 million, or 54%, were transferred in economically significant transactions (i.e., between economically unrelated parties). The majority of the allowances transferred in economically significant transactions were acquired by utilities. In December 2001, trading parties began to use the On-line Allowance Tracking System (OATS). By the end of 2002, OATS recorded 79% of all

transfers electronically over the Internet. All official allowance transactions, as well as data on account balances and ownership, are posted and updated daily at www.epa.gov/airmarkets in order to better inform trading participants and the public of the status of the market. Cumulative market statistics and additional analyses are also available. It should be noted that some allowance transfers are not included in this data because they are not recorded or publicly declared until the allowances are used for compliance purposes.

Program Costs

The cap and trade mechanism in Title IV for reducing SO₂ emissions has led to lower than expected costs as well as to cost savings compared to conventional regulatory approaches. Emissions trading gives electricity generators the flexibility to choose between reducing emissions at their own units and purchasing allowances from other units that can reduce emissions at lower cost. Thus, with efficient trading, each unit faces the same marginal cost of compliance. In addition, there are no technological or permitting restrictions on the means by which SO₂ emissions are reduced. Units under Title IV have many compliance options, including switching to a different type of fuel, switching the grade of fuel, or installing equipment that removes SO₂ after it is created (e.g., scrubbers).

FIGURE 6. SO₂ allowances transferred 1994–2002



Source: EPA analysis





PHASE I COSTS

Early projections of annual Phase I compliance costs ranged from just under \$678 million⁷ to \$1,511 million⁸ (\$2000). These cost estimates took into consideration the allowance trading provisions of Title IV, unlike earlier higher cost estimates for the same level of SO₂ reductions under more restrictive regulatory options. The most recent ex post study of Phase I costs found that in 1995, Phase I units reduced emissions of SO₂ by 3.9 million tons at an estimated cost of \$814 million (\$2000). The cost of this emission reduction was approximately 50% less than it would have been under a command and control program.⁴ An earlier study produced similar results, estimating total compliance costs to be \$940 million (\$2000), although the costs could have been lower still with fully efficient trading.⁹ Both estimates of actual Phase I costs account for the “over-compliance” that occurred in Phase I while building up a bank of unused allowances (used to reduce costs of compliance in Phase II) and are at the lower end of the range of expected results.

PHASE II COSTS

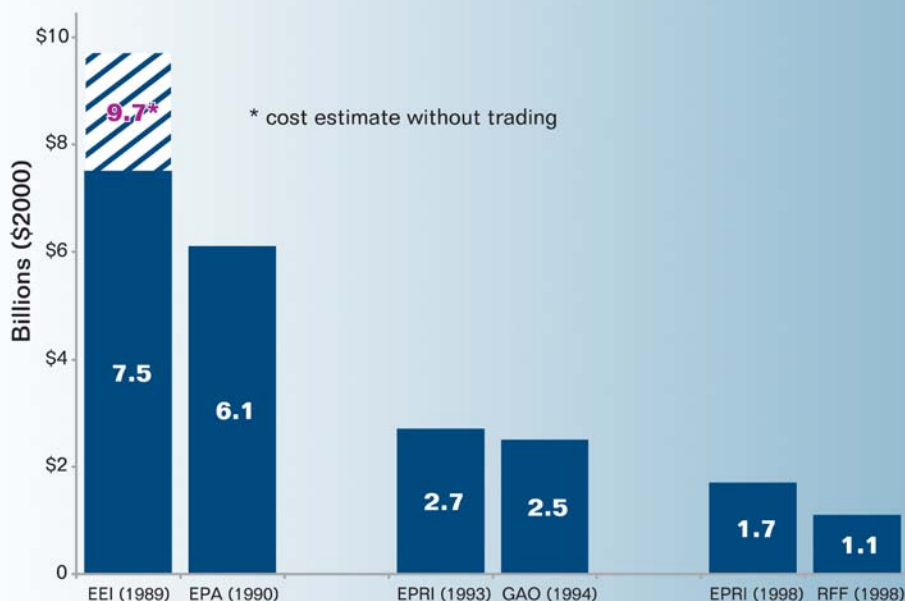
Early proposals to reduce SO₂ emissions that mandated scrubbers or other command and control options were estimated to cost as much as \$7.5 billion/year (\$2000).⁴ The first EPA estimate (1990) for annual Phase II costs was approximately \$6 billion. As the approach of Phase I

neared, the estimates for Phase II costs declined with the General Accounting Office (GAO) revising the estimate to approximately \$2.5 billion per year in 2010 (\$2000)¹⁰ (see Figure 7).

Current estimates of the cost of full implementation of Title IV SO₂ emission reductions are significantly lower than originally estimated. Independent analyses have estimated costs in the range of \$1 to \$2 billion per year in 2010 (\$2000) when the program is nearly fully implemented, substantially less than was predicted in 1990. The most recent estimates provided by Ellerman and by Carlson are \$1.3 to \$1.5 billion per year (\$2000) and \$1.1 billion per year (\$2000) by 2010, respectively.^{4,9} A recent Office of Management and Budget (OMB) analysis estimated costs of the SO₂ program between \$1.1 and \$1.8 billion (\$2000).

NO_x program costs will add to total program costs. EPA expects cost for NO_x reductions to be no more than \$1 billion (\$2000) annually, and based on the limited analysis that has been done, likely to be substantially less.

FIGURE 7. Estimated costs of implementation of Title IV SO₂ emission reductions in 2010
1989–1998



Source: EEI, EPA, EPRI, GAO, and RFF

Several factors are responsible for the relatively low cost SO₂ reductions that have been realized under Title IV.

Low Sulfur Fuel: Switching to low-sulfur coal was the most widely used means of reducing SO₂ emissions under Phase I and is continuing under Phase II.⁵ Historically, low-sulfur sub-bituminous coal from the Powder River Basin of Wyoming and Montana has been relatively inexpensive to mine but costly to transport long distances. In the 1980s, railroad deregulation increased competition and opened the possibility for lower industry freight rates, which would make low-sulfur western coal competitive for units in the Midwest and East. The demand for low-sulfur coal coupled with deregulation helped drive rates down during Phase I. Title IV facilities have taken advantage of reduced costs in complying with the SO₂ limits under both Phase I and Phase II.⁹ Units have also taken advantage of mid-sulfur bituminous coal from the Midwest and Central Appalachia because, despite its higher sulfur content than western coal, mid-sulfur coal requires fewer modifications to boilers and operating procedures.⁵

Scrubber Costs. The costs of scrubbing SO₂ are lower than anticipated.⁵ Prior to Title IV, the initial capital investment for installing scrubbers was expected to be prohibitively high. As Phase I continued, these initial capital costs decreased, as did the marginal cost of scrubbing an additional ton of SO₂ once the technology was installed. It was estimated that scrubbing SO₂ from existing units would cost over \$400/ton (1994) SO₂.⁵ The actual price per ton of SO₂ scrubbers in 1995 was on the order of \$280 (1994); i.e., 40% less than predicted.

Banking. Another aspect to the Title IV program that has led to cost savings in comparison with other regulatory approaches is the option to save or “bank” unused allowances for future use. Over-compliance in Phase I, particularly for those units that installed scrubbers, enabled banking of a large number of allowances forward to Phase II.

This is expected to lower compliance costs during Phase II despite the more stringent national cap on overall SO₂ emissions. According to recent research, the overall amount of banking during Phase I was roughly efficient over time given the current and projected costs of compliance.¹¹

Technological Innovation. The technological improvements that facilitated coal switching and the speed at which they emerged were also not anticipated.⁹ By experimenting with blends of low- and high-sulfur coal that did not lower generating capacity, operators were able to take advantage of the coincidental drop in freight costs for western coal and increased production of mid-sulfur coal in the Midwest. Industry also came up with innovative ways to lower operation and maintenance costs for scrubbers, and ways to increase their utilization rate and efficiency.⁴

Allowance Market. To be fully realized, the anticipated cost-saving benefits of the flexibility provided under Title IV required the creation of an efficient high-volume market for allowances. This has indeed been the case, as discussed above. Since the inception of the program trading has been very active, and trading between distinct organizations has increased in recent years.

ADMINISTRATIVE COSTS

The costs to the government of administering the Title IV SO₂ program are less than in conventional regulatory programs. For example, Title IV's performance-based approach eliminates the need to devise source-specific emission limits, review control technologies, and prepare and approve detailed compliance schedules and permits. In addition, eliminating case-by-case review and approval of each trade (including determining the “useful life” of equipment, the intent of the sources regarding future emission and activity levels, and “real” emission reductions expected to be achieved) greatly reduces the administrative and transaction costs associated with emissions trading programs.¹² During Phase I, costs of the program were roughly \$12 million/year or approximately \$1.50/ton of pollution reduced.¹³ Most of the functions in the allowance market are carried out by private entities; the government's role is primarily to ensure that units are monitoring emissions throughout the year and to ensure that each unit has enough allowances to cover emissions at the end of the year. In 2003, EPA estimates that sources, as a group, spent approximately \$250 million on administrative functions of the program, including allowance transfers, permitting, emissions monitoring, compliance, and other administrative costs.





Program Assessment

EMISSIONS MONITORING

Title IV includes strict emission monitoring requirements to guarantee compliance with both the cap and trade and emission rate limit components of the program. Most affected sources installed required monitoring equipment on time; the few that did not were subject to stringent emission estimation procedures. The monitoring regulations that implement Title IV include strict procedures to estimate emissions when approved methods are not used. These procedures, which overestimate total emissions, provide a strong incentive to install and maintain accurate monitoring equipment, minimize emission monitor downtime, and ensure that emissions are not under-reported. All monitors are required to meet stringent initial and ongoing performance standards to demonstrate the accuracy, precision, and timeliness of their measurement capabilities. The monitors used by sources to comply with Title IV have achieved an unparalleled level of performance with respect to all of these criteria.

Sources have now completed installation of all continuous emission monitors (CEMs) required under the Acid Rain Program. Coal-fired units must use CEMs to measure concentrations of SO₂ and NO_x, as well as volumetric flow, to determine hourly mass emissions of SO₂, hourly NO_x emission rates, and hourly heat input. Coal-fired units may estimate their CO₂ emissions, but virtually all have chosen to use CEMs to measure them instead. Oil- and gas-fired steam units may either use CEMs or they may use certified fuel flow meters and frequent fuel sampling analyses to determine the hourly SO₂ and CO₂ mass emissions and hourly heat input. Most oil- and gas-fired steam units are required to use CEMs to determine hourly NO_x emission rates. However, for an oil- or gas-fired peaking unit, the owner or operator may develop a correlation curve between heat input and NO_x emission rate, in lieu of installing a CEM. If this option is selected, the hourly heat input is monitored using a certified fuel flow meter, and the correlation curve is used to estimate the hourly NO_x emission rate.¹⁴

One measure of the accuracy of a CEM is the relative accuracy test audit (RATA), which is required for initial certification of a CEM and on at least an annual basis, thereafter. The RATA ensures that the installed monitor measures the “true” value of a pollutant by comparing the monitor to a reference method, which simultaneously measures the stack gas pollu-

tant. All monitoring systems must meet a relative accuracy standard allowing no more than 10% deviation from the true value in order to continue to be used for emissions reporting. Further, if the CEM is biased low compared to the true value, a bias adjustment factor must be applied to all future data from that monitoring system to ensure there is no underreporting. This “self-correcting” provision, coupled with daily quality assurance testing requirements, creates a strong incentive to maintain monitor performance (since failure to meet the accuracy requirements can result in sources being required to surrender more allowances at year’s end) and helps insure that each allowance is truly equivalent to a single ton of SO₂.

AIR QUALITY, DEPOSITION, AND ECOLOGICAL MONITORING

Air quality and deposition monitoring are also important components of the overall implementation of Title IV. Several monitoring networks designed to measure changes in air quality and acid deposition as a result of emission reductions are currently in operation. There is also a surface water monitoring network in acid-sensitive areas in the Eastern U.S. that measures changes in lake and stream chemistry as a result of changes in emissions and atmospheric deposition. Finally, many researchers continue to conduct studies to assess the impacts of emission reductions on lakes, streams, forests, and coastal ecosystems. Together, this information allows policymakers to accurately assess the impact of Title IV and other air quality policies and to determine if the environmental goals are being achieved. Additional and more detailed information about the monitoring networks is presented in Chapter 2. In addition, there is ongoing work in the U.S., Canada, and Mexico to further evaluate the air quality and deposition impacts of pollutants that cross over international boundaries.

Developing the Infrastructure for Long-Term Monitoring

There are two primary national monitoring networks that measure regional trends in acid deposition and air quality. The National Atmospheric Deposition Program (NADP) measures acid and other chemical concentrations and annual deposition in precipitation, and the Clean Air Status and Trends Network (CASTNET) measures air quality concentrations and dry deposition of nitrogen and sulfur compounds. The data from these monitoring networks are the primary way for researchers and policy analysts to assess the environmental benefits of Title IV and any other regional or national emission reduction programs such as the NO_x State Implementation Plan (SIP) call.

PLANNING FOR AN AGING NETWORK: NADP'S REFURBISHMENT

The original NADP deposition monitoring stations were installed in 1978, with a large portion of the network in place by 1984. The current sampling equipment has been operating continuously in the field for an average of 17 years without substantial upgrade or refurbishment. A major refurbishment and/or replacement program is needed to prevent the aging equipment from limiting the network's ability to collect high quality data. In order to begin the process of upgrading the network, testing of off-the-shelf modern precipitation recording gauges is now underway. The design of a new deposition sampler began in 2000. The overall objective is to develop and deploy,

on a network-wide basis, a modern and more flexible deposition sampling system, one that would not only support all current NADP sampling needs, but also provide the capability to sample additional pollutants as the need arises.

ADVANCING CASTNET'S MONITORING CAPACITY

The original CASTNET monitoring stations were established in 1987. CASTNET plays a vital role in providing regional concentrations of important particle and gaseous chemical species, deposition estimates of important acidic species, rural ozone, and regional transport. CASTNET continues to provide accountability and performance measure-related information for the Acid Rain Program and is in position to provide deposition and air quality baselines to support future accountability and program evaluation needs (whether regulatory or legislative). As such, both near- and long-term program goals involve advancing the monitoring and assessment capabilities of the network. Specifically, plans for CASTNET include a multi-agency effort between EPA, NOAA, The National Park Service and the United States Forest Service to add high-resolution, continuous measurements of gases and particles to the suite of measurements conducted at each site. These additional measurements are important in expanding our understanding of fine particulate formation, transport, and air quality model evaluation. This change will also provide critical information for implementation of an integrated monitoring strategy for key monitoring programs in the U.S. (e.g., IMPROVE, NADP) and Canada.



Chapter 2: Results of the Acid Rain Program: Status and Trends of Emissions and Environmental Impacts (1990–2002)

Both SO₂ and NO_x emissions from power generation sources have significantly declined under Title IV. In 2002, SO₂ emissions from Title IV-affected sources totaled 10.2 million tons and NO_x emissions from all Title IV-affected sources totaled 4.5 million tons, down 35% and 33% respectively from 1990 levels. Sources in states with the highest emissions continue to reduce their emissions the most, and there have been no significant geographic shifts in emissions. The benefits of these emission reductions include improvements in air quality (which are expected to lead to significant human health benefits), broad-scale reductions in sulfate deposition, and improvements in visibility. While surface waters in some areas have begun to show signs of recovery from acidification, acidification is still occurring in many areas. Although there have been no broad-scale regional reductions in nitrogen deposition, nitrogen deposition has declined in some areas, benefiting some nitrogen-sensitive forests and coastal waters and acid-sensitive lakes and streams.



Emissions

SO₂ EMISSIONS

SO₂ emissions declined significantly in 1995, the first year Title IV took effect. Emissions climbed slightly from 1995 levels during the late 1990s but remained far below the number of allowances allocated. These “extra” reductions allowed sources to build up a large bank of unused allowances that could be used in the future when the emission cap decreased during Phase II. Beginning in 2000, the first year of Phase II, sources complied with the lower cap by

decreasing emissions significantly as well as by using some of their banked or stored allowances. In 2002, the 3,208 sources in the SO₂ program had reduced their SO₂ emissions by 41% (7.1 million tons) compared to 1980 levels and 35% (5.5 million tons) compared to 1990 levels. Figure 8 shows the trend in SO₂ emissions since 1980 for all affected sources.

The electric utility industry is by far the largest single source of SO₂ emissions, accounting for approximately 69% of total SO₂ emissions nationwide in 2001¹⁵ (www.epa.gov/ttn/chief/trends/index.html). In addition to the significant reductions from the electric power generation sector, reductions in SO₂ emissions from other sources, including smelters and sulfuric acid manufacturing plants, and use of cleaner fuels in residential and commercial burners, have contributed to the 39% decline of SO₂ emissions from all sources since 1980 (EPA Web site, 2003). Figure 9 shows the trend in total SO₂ emissions from all sources since 1980.

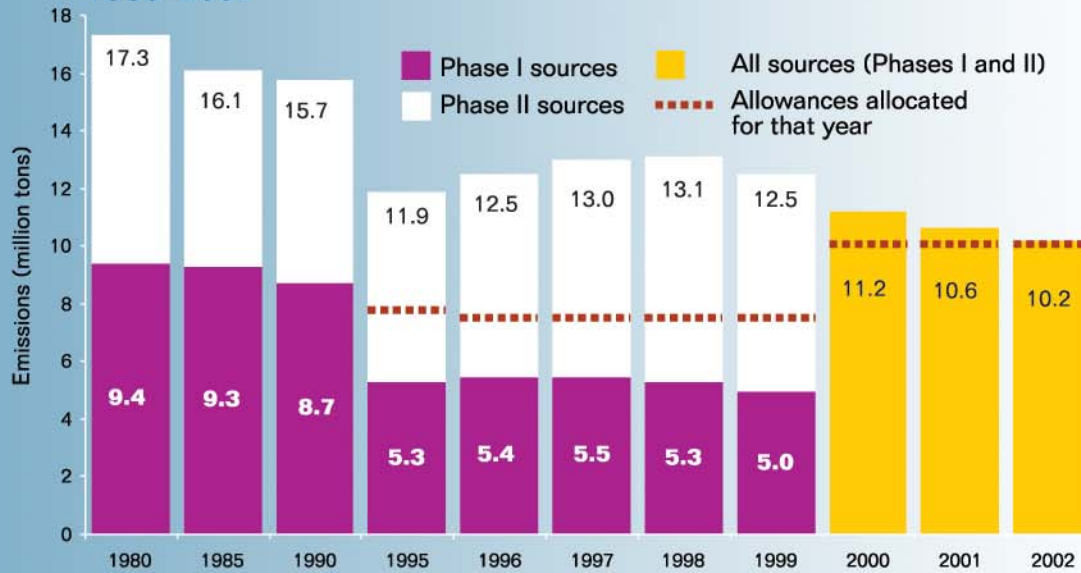
NO_x EMISSIONS

NO_x emissions from all Title IV sources dropped approximately 1.6 million tons between 1990 and 1996, when Phase I of the Acid Rain NO_x program was implemented. Subsequently, NO_x emissions remained fairly steady through 1998 before dropping significantly in 1999 and again in 2000 to comply with the stricter emission limits under Phase II. By 2002, emissions from the 1,048 NO_x program affected sources were 27% (1.5 million tons) lower than they had been in 1990. NO_x emissions for all 3,208 Title IV units were 33% (2.2 million tons) lower than they had been in 1990.

Title IV of the 1990 Clean Air Act requires the NO_x program to achieve a 2 million ton reduction in emissions from projected 2000 NO_x emission levels without Title IV. Total NO_x emissions from all Title IV affected units surpassed that goal by 1 million tons in 2000 (see Figure 10).

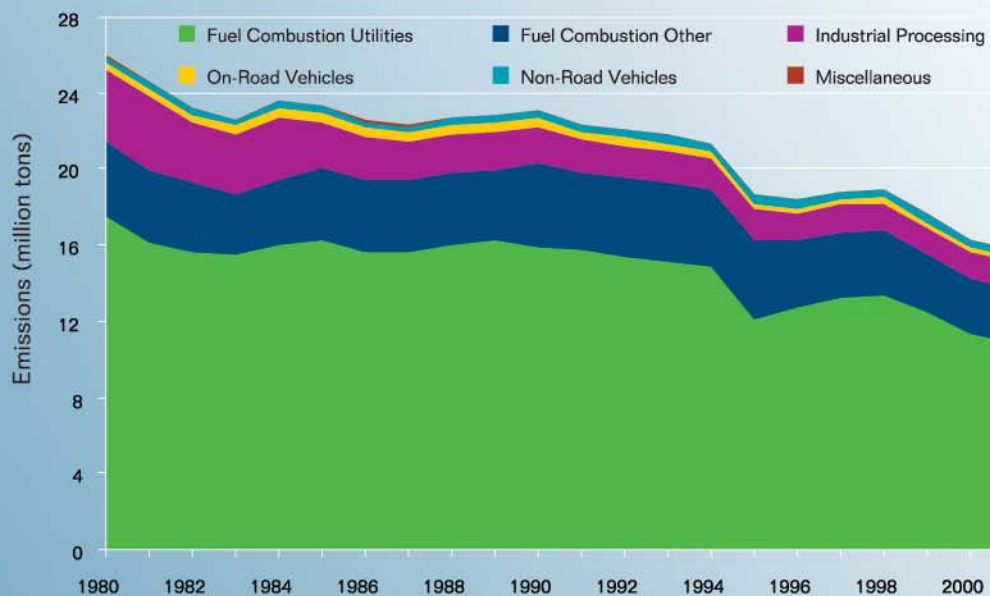
These reductions have been achieved by reducing the amount of NO_x emitted per unit of heat input and despite the fact that the amount of fuel burned to produce electricity in power plants has increased 30% since 1990. As illustrated in Figure 11, many states with increasing

FIGURE 8. SO₂ emissions from all affected sources
(electric generating units)
1980–2002



Source: EPA

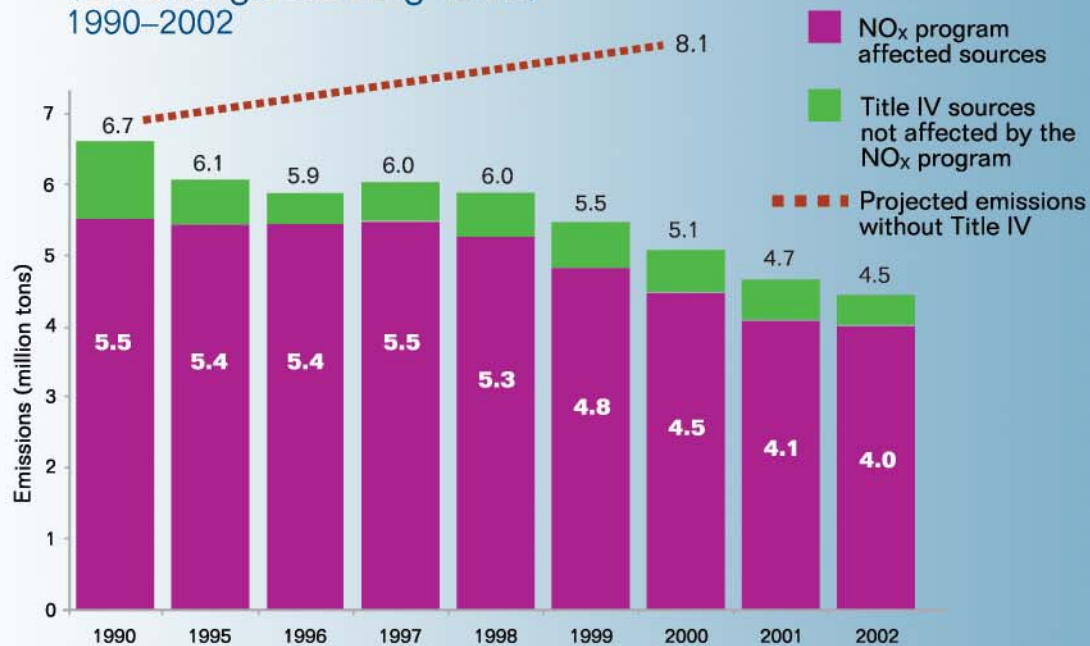
FIGURE 9. SO₂ emissions from all sources
1980–2001



Source: EPA

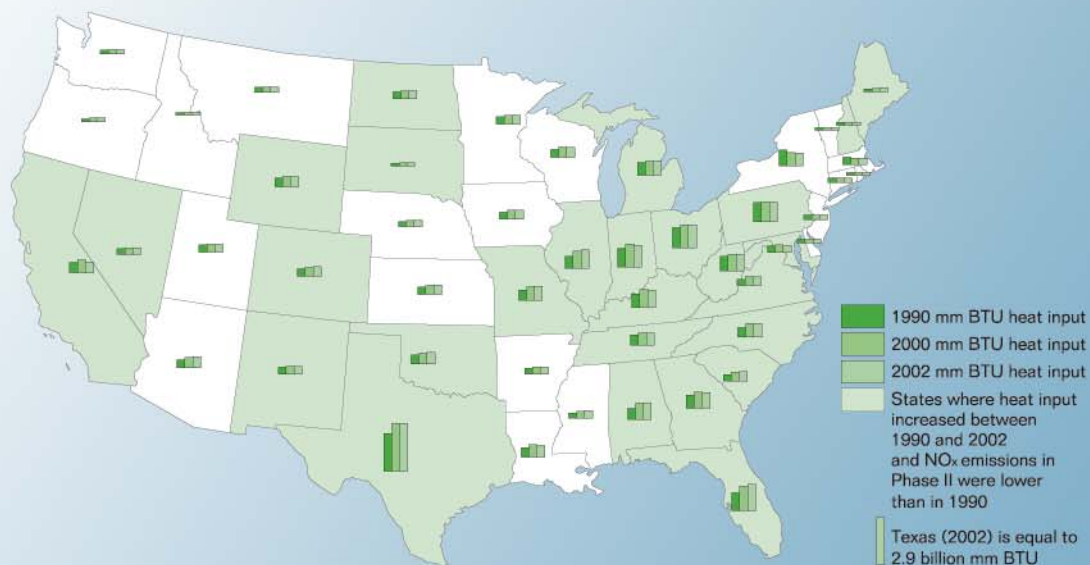


FIGURE 10. NO_x emissions from all affected sources (electric generating units) 1990–2002



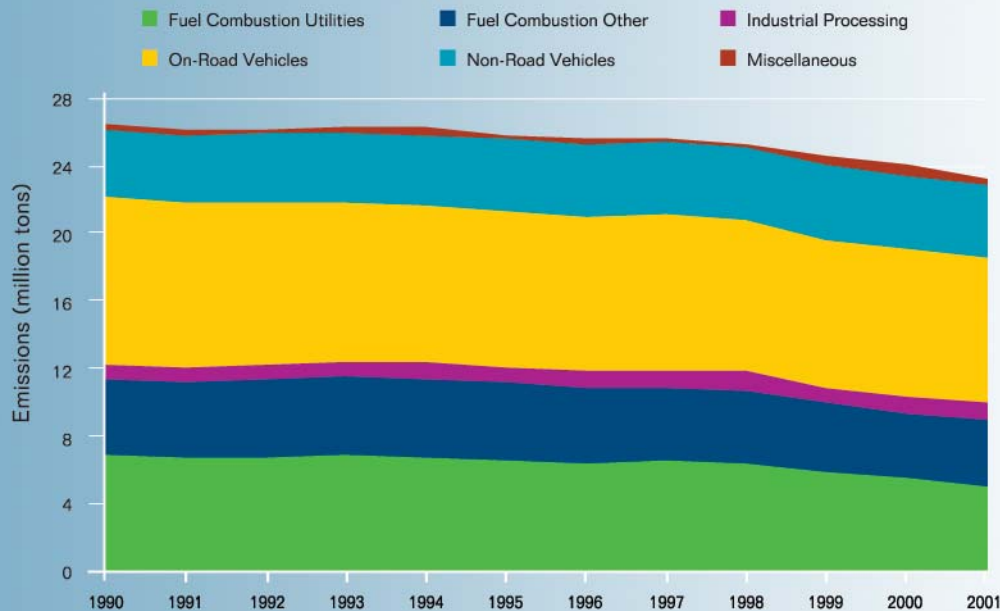
Source: EPA

FIGURE 11. Energy use and NO_x emissions by state 1990–2002



Source: EPA

FIGURE 12. NO_x emissions from all sources
1990–2001



Source: EPA



electricity production had lower total NO_x emissions in 2002 as compared to 1990 levels. Without further reductions in emissions rates or institution of a cap on NO_x emissions, however, NO_x emissions from power plants could rise as more fossil fuels are used to create energy in most areas of the country.

NO_x emissions come from a wide variety of sources including those affected by Title IV. In 2001, NO_x emissions from electric power generation accounted for approximately 22% of NO_x emissions from all sources (4.9 million tons). NO_x emissions from transportation sources were 56% of NO_x emissions from all sources (12.4 million tons). Nationally, NO_x emissions have decreased 12% (3.2 million tons) between 1990 and 2001. This occurred in spite of an increase of 10% in NO_x emissions from non-road vehicles since 1990 that has been more than offset by the emission decreases from electric power generation and other fuel combustion sources. This is due to a variety of federal and state emission reduction programs (including Title IV, the Ozone Transport Commission NO_x Budget Trading Program, and anticipation of

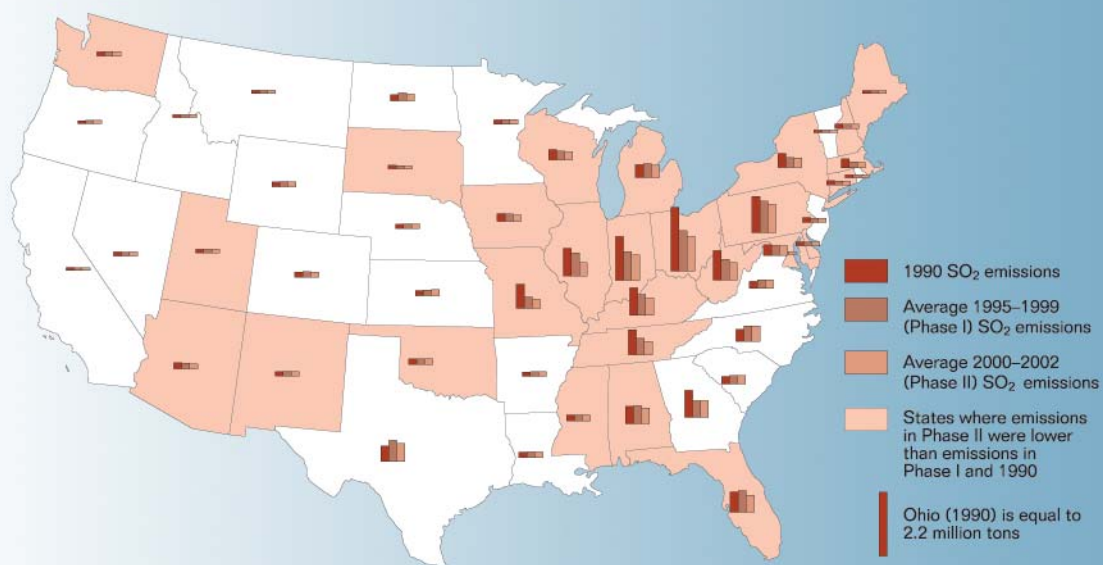
the NO_x SIP call) and reductions from on-road vehicles (EPA Web site, 2003). In the past few years, EPA has promulgated several rules to reduce SO₂ and NO_x emissions from mobile sources, including the Heavy Duty Diesel Rule and the Non-Road Rule. As these rules take effect they will significantly reduce emissions from trucks and other diesel and off-road vehicles (see Figure 12). In addition, new rules for stationary sources (the Clean Air Interstate Rule, the Clean Air Mercury Rule, and the Clean Air Visibility Rule), as well as State plans to attain the fine particle and ozone NAAQS, will also significantly reduce future NO_x emissions.

Geographic Distribution of Emissions from Power Generation

GEOGRAPHIC TRENDS IN SO₂ EMISSIONS

Total SO₂ emissions from power generation have decreased approximately 35% under the cap and trade approach since 1990. Emission reductions are taking place throughout the country; the geographic distribution of SO₂ emissions has not changed significantly since 1990.¹⁶ Figure 13 compares state SO₂ emission trends from power generation before implementation of Title IV (1990), during Phase I of Title IV (1995–1999 average), and in Phase II to date (2000–2002 average).

FIGURE 13. SO₂ emission trends from power generation facilities by state 1990–2002



Source: EPA

Several geographic trends are evident. Although most SO₂ emissions still occur in the midwestern U.S., it is important to note that, over time, this same region has also seen the most significant decrease in SO₂ emissions in the country (see Figure 13). This confirms an important principle of the cap and trade approach: reducing emissions is cheapest for the largest sources. These sources will, therefore, reduce emissions before others in the industry and take advantage of their ability to sell excess allowances to other sources where emission reductions are more expensive.¹⁷ The highest SO₂ emitting states in 1990 (Ohio, Indiana, and Pennsylvania) reduced emissions an average of 39% in Phase I of the program (48%, 46%, and 24%, respectively) compared to 1990 levels. Other states in the region show similar trends since 1990. SO₂ emissions decreased 57% in Illinois, 41% in Kentucky, 70% in Missouri, 53% in Tennessee, and 45% in West Virginia. The 27 shaded states represent states where SO₂ emissions in Phase II (2000–2002) were lower than both 1990 levels and the 1995–1999 Phase I average. Most SO₂ emission reductions during Phase I occurred in approximately a dozen states in the Eastern U.S. (Phase I affected the larger, higher emitting utilities in the eastern half of the country). Unlike the SO₂ emission reductions achieved during Phase I, Phase II reductions are geographically more widespread, occurring in a larger number of southeastern and some western states.

In 20 mostly western and southern states, average SO₂ emissions in Phase I were higher than they had been in 1990. This is due to the large number of Phase II sources in these states that were not required to control for SO₂ until 2000. In the 2000–2002 period (Phase II), emissions in these states declined as their sources became subject to the provisions of the Acid Rain Program. For example, SO₂ emissions in Texas increased from 1990–1999 because no Texas sources were affected by Title IV at that time. SO₂ emissions in the state decreased more than 100,000 tons in Phase II when Title IV requirements took effect for Texas sources. In fact, sources in all the states where average emissions in Phase I were higher than emissions in 1990 collectively reduced their emissions approximately 500,000 tons in Phase II (2000–2002).

In addition, some sources increased their emissions since 1990 due to increasing utilization of units. However, over half these units actually decreased their emission rate, indicating that increases in demand for elec-

tricity caused those emission increases. These emission increases, while not insignificant, were more than offset by the emission reductions that have occurred since 1990. In the 16 states where state-wide emissions increased, the emission increases totaled 430,000 tons of SO₂ between 1990 and 2002; over that same period of time, the remaining states reduced SO₂ emissions more than 13 times that much, by 5.5 million tons.

GEOGRAPHIC TRENDS IN NO_x EMISSIONS

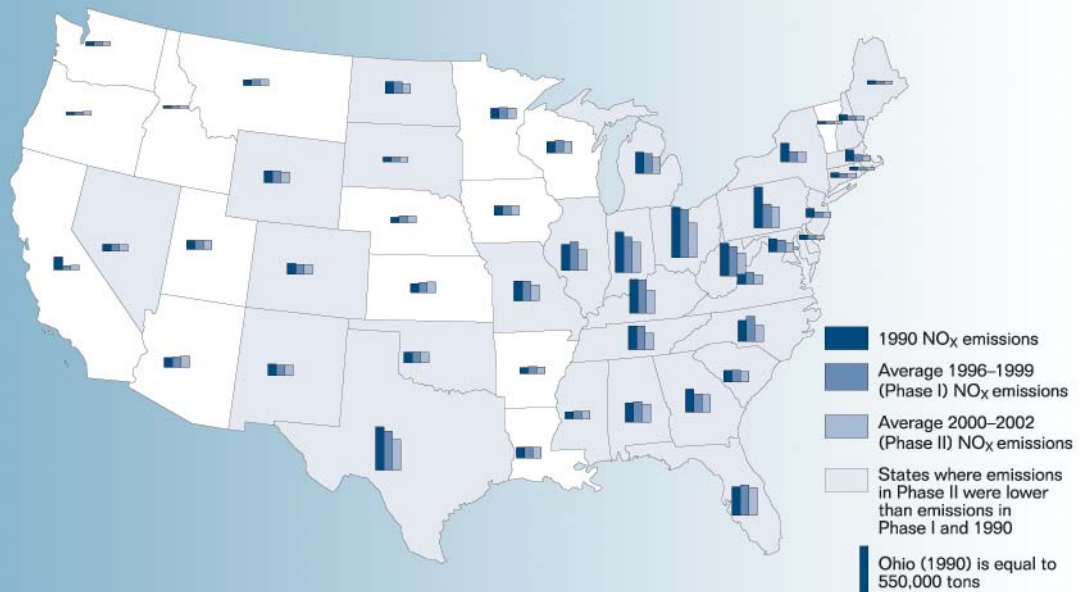
Total NO_x emissions from NO_x program affected sources (coal-fired) have decreased approximately 27% since Title IV was authorized by Congress in 1990. The geographic distribution of NO_x emissions has not changed significantly since 1990.¹⁶ Even though most emission reductions have taken place in the areas of the country with the highest NO_x emissions, these reductions have not resulted in a large change in the pattern of NO_x emissions in the U.S. NO_x emission reductions since 1999 are due in part to implementation of the OTC NO_x Budget Program, the NO_x SIP call, and several state

reduction programs as well as Phase II of Title IV. Figure 14 displays bar graphs illustrating relative state NO_x emission trends from power generation sources affected by the NO_x program before Title IV (1990), during Phase I (1996–1999 average), and in Phase II (2000–2002 average).

Several geographic trends are evident. NO_x emissions were lower in 34 states in Phase II compared to 1990 levels, with the greatest reduction occurring in the Eastern United States. In 1990, the highest NO_x emissions occurred in the midwestern and southern regions of the U.S. (see Figure 14). By 2002, emissions in many of these states had been significantly reduced from 1990 levels. The states with the highest emissions in 1990 (Ohio, Texas, and Pennsylvania), achieved an average reduction of 38% (33%, 30%, and 52%, respectively) in Phase II compared to 1990. Other states in the region show similar trends since 1990. NO_x emissions decreased 27% in Indiana, 23% in Illinois, 35% in Kentucky, 34% in Tennessee, and 31% in West Virginia. The 32 shaded states had lower average NO_x emissions in Phase II compared to both 1990 levels and the 1996–1999 Phase I average. NO_x reductions occurred predominantly in the northeastern U.S. during Phase I. In Phase II, NO_x reductions are geographically more extensive and occur in a larger number of southern and midwestern states.



FIGURE 14. NO_x emission trends from power generation facilities by state 1990–2002



Source: EPA

In several states, average NO_x emissions during Phase I were higher than they had been in 1990. This is due to the large number of Phase II sources in these states that were not required to control NO_x emissions until 2000. In the 2000–2002 period (Phase II), emissions in many of these states have declined. There are also several states where average Phase II NO_x emissions were higher than emissions in 1990 and/or the Phase I average. This is because the rate-based Title IV NO_x limits on coal-fired power plants do not limit total emissions of NO_x in the way that total emissions of SO₂ are limited. Since heat input (or fuel use) increased in those states due to additional power generation, overall NO_x emissions also increased.

Air Quality, Deposition, and Visibility

Many government agencies, states, and universities work together to monitor the effects of emissions changes on air quality and acid deposition. A mosaic of national air quality and deposition monitoring networks has evolved to provide scientists and policymakers robust data for assessing the effectiveness of emission reduction programs and to determine environmental effects, particularly those caused by regional

sources of emissions for which long range transport plays an important role. The information derived from these networks is used to determine how well existing air pollution control strategies are working and whether additional emission reductions are required to improve public health and facilitate ecosystem recovery. Measurements from these networks are also important for understanding non-ecological impacts of air pollution such as visibility impairment and damage to materials (e.g., historical sites and cultural monuments). Figure 15 shows the monitoring station locations of the primary long-term air quality and atmospheric deposition networks: The National Atmospheric Deposition Program/National Trends Network (NADP/NTN), CASTNET, and the Interagency Monitoring of Protected Visual Environment (IMPROVE) program. Figure 15 also includes a table listing the major chemical species measured by these networks as well as the other networks discussed below.

Primary Air Quality and Atmospheric Deposition Monitoring Networks

A mosaic of national air quality and deposition monitoring networks has evolved to provide scientists and policymakers robust data on the fate and transport of regional sources of emissions, especially those for which long range transport plays an important role. Although it may appear that some networks perform redundant measurements, this overlap in fact provides important quality assurance information that is used to identify and account for biases in each of the measurement networks. The information derived from these networks is used to determine how well existing air pollution control strategies are working and whether additional emissions reductions are required to improve public health, improve visibility, and facilitate ecosystem recovery.

WET DEPOSITION MONITORING

NADP/NTN is a nationwide network of predominantly rural precipitation monitoring stations.

Operating since 1978, the network collects weekly wet acid deposition data to determine geographic patterns and temporal long-term trends. NADP/NTN is responsible for measuring the wet deposition component of total pollution loads across the U.S. The network is a collaborative effort between many different organizations, including U.S. Geological Survey (USGS), U.S. Environmental Protection Agency (USEPA), National Park Service (NPS), U.S. Department of Agriculture (USDA), National Oceanic and Atmospheric Administration (NOAA), State Agricultural Experiment Stations (SAES), tribes, universities, and industry. NADP/NTN consists of over 230 monitoring stations spanning the continental United States, Alaska, Canada, Puerto Rico, and the Virgin Islands. The Atmospheric Integrated Research Monitoring Network (AIRMoN), a research-based subnetwork of NADP, consists of nine monitoring stations that collect daily precipitation samples. The daily samples are analyzed for the same pollutants as NADP/NTN and are primarily used to identify source-

receptor relationships in atmospheric models. Quality assurance procedures are followed for all aspects of NADP field and laboratory operations. Quality assured data are available from the NADP Web site, <http://nadp.sws.uiuc.edu/>.

AMBIENT AND DRY DEPOSITION MONITORING

CASTNET is a long-term atmospheric deposition monitoring network that measures changes in ambient air quality and atmospheric deposition over broad regions of the U.S. Operating since 1987, CASTNET has evolved into a robust monitoring program which now comprises over 80 monitoring stations nationwide. Sites are located predominantly in rural locations. EPA operates most of the monitoring stations; however, NPS operates 30 stations in cooperation with EPA. CASTNET measures weekly average atmospheric concentrations of the major pollutants contributing to acid deposition, hourly concentrations of ambient ozone levels, and meteorological conditions. CASTNET estimates dry deposition or flux based on measured ambient air concentrations and modeled deposition velocity. Deposition velocity is inferred through the multilayer model (MLM) which accounts for the influence of meteorological conditions and vegetation on dry deposition processes. CASTNET data measured at point locations are used in conjunction with the NADP/NTN data to infer geographic patterns and long-term temporal trends in total (dry plus wet) atmospheric deposition. Quality assurance procedures are followed for all aspects of CASTNET field and laboratory operations. Quality assured data are available at www.epa.gov/castnet.

VISIBILITY MONITORING

IMPROVE is a long-term monitoring network that measures current visibility conditions, tracks changes in visibility and determines the causes of visibility impairment in national parks and wilderness areas. IMPROVE was established in 1985 to aid the development of federal and state implementation plans to protect visibility in Class I areas as stipulated in the 1977 amendments to the Clean Air Act. IMPROVE began collecting data in 1988 at 20 Class I areas. The network expanded to monitor the impacts of the Regional Haze Rule and now

consists of 167 sites nationwide. IMPROVE is a collaborative monitoring effort directed by a steering committee comprised of representatives from NPS, USEPA, USFS, FWS, NOAA, Bureau of Land Management, and state and regional air organizations. Every IMPROVE site deploys an aerosol sampler to measure speciated fine aerosols and PM₁₀ mass. Select sites also deploy transmissometers and nephelometers to measure light extinction and scattering respectively, as well as automated camera systems to measure the "scene." Light extinction coefficients and the deciview indices used to report visibility data are calculated from relative humidity and the measurements of the five key species: sulfates, nitrates, organic carbon, elemental carbon, and crustal material at each site. Data and additional information about IMPROVE are available at <http://vista.cira.colostate.edu/improve/>.

AIR QUALITY MONITORING

State and Local Air Monitoring Stations (SLAMS) and National Air Monitoring Stations (NAMS) are designed to judge compliance with ambient air quality standards; activate emergency control procedures that prevent or alleviate air pollution episodes; and observe pollution trends throughout the region. The information collected also provides a database for research on urban, land use, and transportation planning; development and evaluation of abatement strategies; and development and validation of dispersion models.

The SLAMS/NAMS network performs measurements primarily in urban areas where air quality is influenced primarily by local sources. Some sites are located away from urban areas to characterize regional air quality. SLAMS consists of approximately 4,000 monitoring stations whose size and distribution are largely determined by the needs of state and local air pollution control agencies to meet their respective SIP requirements. NAMS (1,080 stations) are a subset of the SLAMS network with emphasis on areas of maximum concentrations and high population density. Additional information on SLAMS/NAMS is available at www.epa.gov/oar/oaqps/qa/monprog.html.

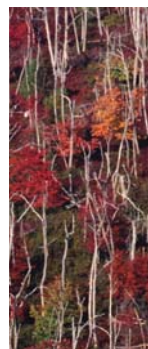


FIGURE 15. Location of NADP/NTN, CASTNET, and IMPROVE monitoring sites and pollutants measured by major networks



Source: NADP/NTN and CASTNET

AIR QUALITY AND ACID DEPOSITION MEASUREMENTS

CHEMICALS	WHY ARE THESE MEASURED BY THE NETWORKS?		NETWORK COVERAGE
SO ₂	Sulfur Dioxide	Indicator of ambient air quality; measured in dry monitoring networks; major precursor to acid deposition	CASTNET; AIRMoN-dry; SLAMS/NAMS
SO ₄ ²⁻	Ionic Sulfates, Particulate Sulfates	Indicators of ambient air quality and sulfur deposition; regional transport; correlated with sulfur dioxide emissions; measured in wet and dry monitoring networks	NADP/NTN; CASTNET; NADP/AIRMoN; IMPROVE
NO ₃ ⁻	Ionic Nitrates, Particulate Nitrates	Indicators of ambient air quality and nitrogen deposition; correlated with NO _x emissions; measured in wet and dry monitoring networks	NADP/NTN; CASTNET; NADP/AIRMoN; IMPROVE
HNO ₃	Nitric Acid	Strong acidic compound; main component of dry nitrogen deposition; measured in dry monitoring networks	CASTNET; AIRMoN-dry
NH ₄ ⁺	Ionic Ammonium, Particulate Ammonium	Indicators of ambient air quality and nitrogen deposition; associated with production of fine particles; aerosol ammonium is associated with sulfate ion; can play a role neutralizing atmospheric acidic species; measured in wet and dry monitoring networks	NADP/NTN; CASTNET; NADP/AIRMoN
H ⁺	Ionic Hydrogen	Indicator of acidity in precipitation; measured in wet deposition monitoring networks	NADP/NTN; NADP/AIRMoN
Ca ²⁺ Mg ²⁺ K ⁺ Na ⁺	Calcium Magnesium Potassium Sodium	These base cations are indicators of the ability to neutralize acids in precipitation; also play an important role in plant nutrition and soil productivity	NADP/NTN; NADP/AIRMoN; CASTNET

AIR QUALITY: SULFUR

Analyses of regional monitoring data from CASTNET show the geographic pattern of SO_2 and airborne sulfate in the Eastern United States, where concentrations from power plants are highest. Three-year mean annual concentrations of SO_2 and sulfate from a set of 34 CASTNET long-term monitoring sites were compared from 1989–1991 and 2000–2002. In 1989–1991, prior to implementation of Phase I of Title IV, the highest ambient concentrations of SO_2 in the East were observed in western Pennsylvania, and along the Ohio River Valley in the vicinity of Chicago, Illinois, and Gary, Indiana. The highest ambient sulfate concentrations, greater than 7 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$), were observed in this area and in northern Alabama. Most of the Eastern U.S. experienced annual ambient sulfate concentrations greater than $5\mu\text{g}/\text{m}^3$.

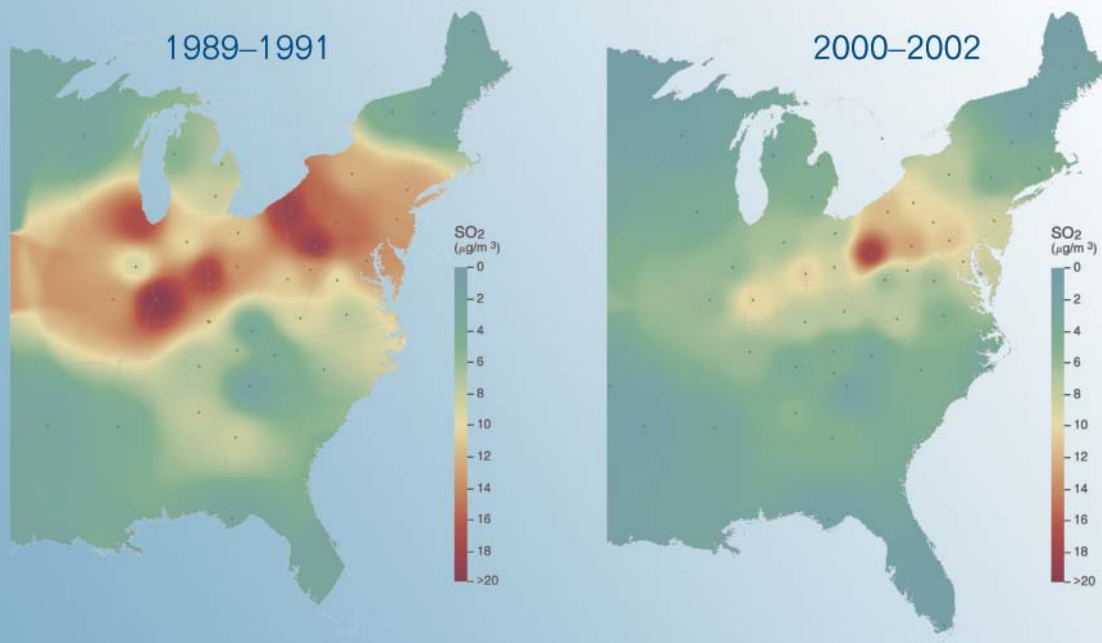
During the late 1990s following implementation of Phase I, dramatic regional improvements in SO_2 and sulfate air quality

were observed at CASTNET sites throughout the Eastern U.S. Ambient concentrations of SO_2 in 2000–2002 decreased 45% in the Midwest, 40% in the Northeast and 30% in the mid-Atlantic compared to concentrations in the early 1990s (see Figure 16). Other researchers, using different statistical methods, have also reported reductions in SO_2 concentrations of 30–40% in the northern mid-Atlantic and Midwest.¹⁸ The largest decreases in ambient SO_2 concentrations were noted in high emissions and concentration areas (e.g., vicinity of Chicago and throughout Indiana, Ohio, Pennsylvania, Kentucky, and West Virginia). The highest SO_2 concentrations observed in the rural parts of the United States are now concentrated in eastern Ohio and southwestern Pennsylvania.

For ambient sulfate, both the size of the affected region and magnitude of the highest concentrations were dramatically reduced following implementation of Title IV. Sulfate concentrations decreased up to 30% in the Midwest and Northeast and 25% in the mid-Atlantic compared to concentrations observed in the early 1990s (see Figure 17). The largest decreases were observed along the Ohio River Valley in Illinois and Pennsylvania. These reductions have also been confirmed by other researchers using different statistical methods.¹⁸



FIGURE 16. Comparison of annual ambient sulfur dioxide (SO_2) concentrations in the rural eastern United States



Source: CASTNET

The urban monitoring networks (SLAMS/NAMS) also detected the environmental signal from Title IV SO₂ emission reductions. Analyses of urban monitoring data from 480 monitoring stations show a decreasing trend in SO₂ in the atmosphere following implementation of Title IV. Between 1992 and 2001, annual arithmetic mean concentrations of atmospheric SO₂ decreased 35%.¹⁶

AIR QUALITY: NITROGEN

Emissions of NO_x are transformed in the atmosphere into a series of pollutants, including nitric acid vapor (HNO₃) and nitrates (NO₃). From the perspective of acid deposition, nitric acid is a key chemical species, for which the rural air quality and dry deposition monitoring networks now have an extensive record. While there is strong evidence of statistically significant declining trends in the concentrations of SO₂ and sulfate, trends in nitrogen concentrations have not been as pronounced.

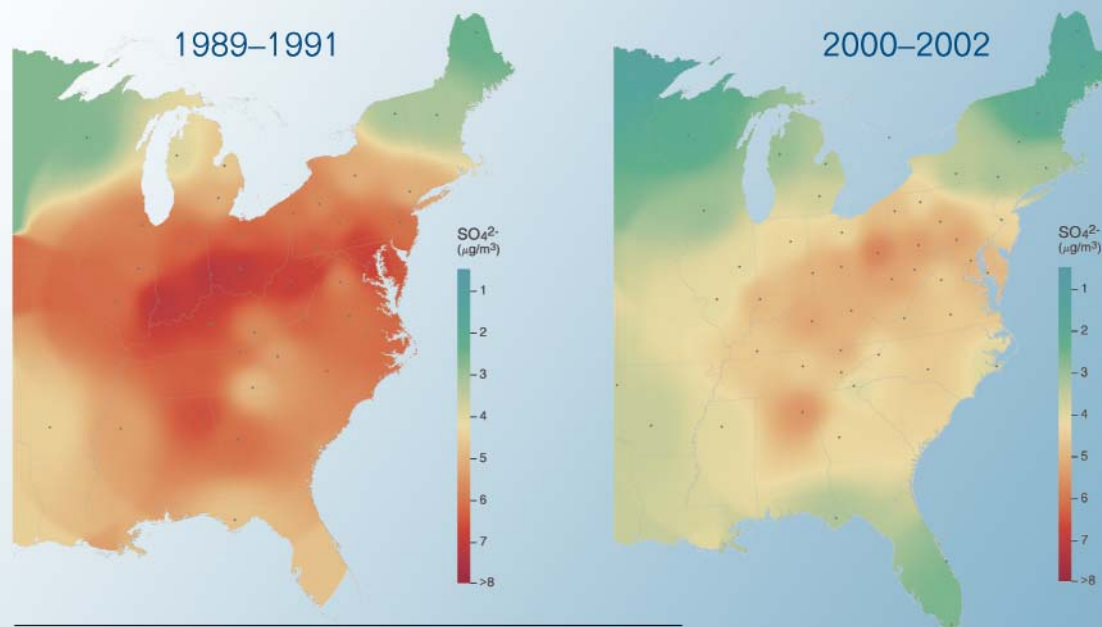
Atmospheric nitrogen concentrations are a result of emissions of several different forms of nitrogen from many different types of sources; therefore, they tend to exhibit a more complicated pattern than sulfur concentrations. Nitric acid concentrations, for example, are highest in eastern Ohio and south central Pennsylvania/north central Maryland, areas with high emissions from power plants.

Ammonium concentrations, in contrast, are highest from Ohio west to Missouri and Iowa and in northern Alabama as well as central Pennsylvania. Nitrate concentrations are highest even further west, in southern Wisconsin/northern Illinois and westward into the Plains, areas with large amounts of agricultural activity.

Scientists have not reported any evidence of a statistically significant decreasing trend in nitric acid concentrations over the past 15 years, but a recent analysis of CASTNET data does indicate that nitric acid concentrations may be lower than they were in the 1989–1991 timeframe. CASTNET data indicate reductions of nitric acid concentrations between 1989–1991 and 2000–2002 of approximately 10% in the Northeast, mid-Atlantic, Southeast, and Midwest, and approximately 25% in the North Central and South Central Plains states (see Figure 18).

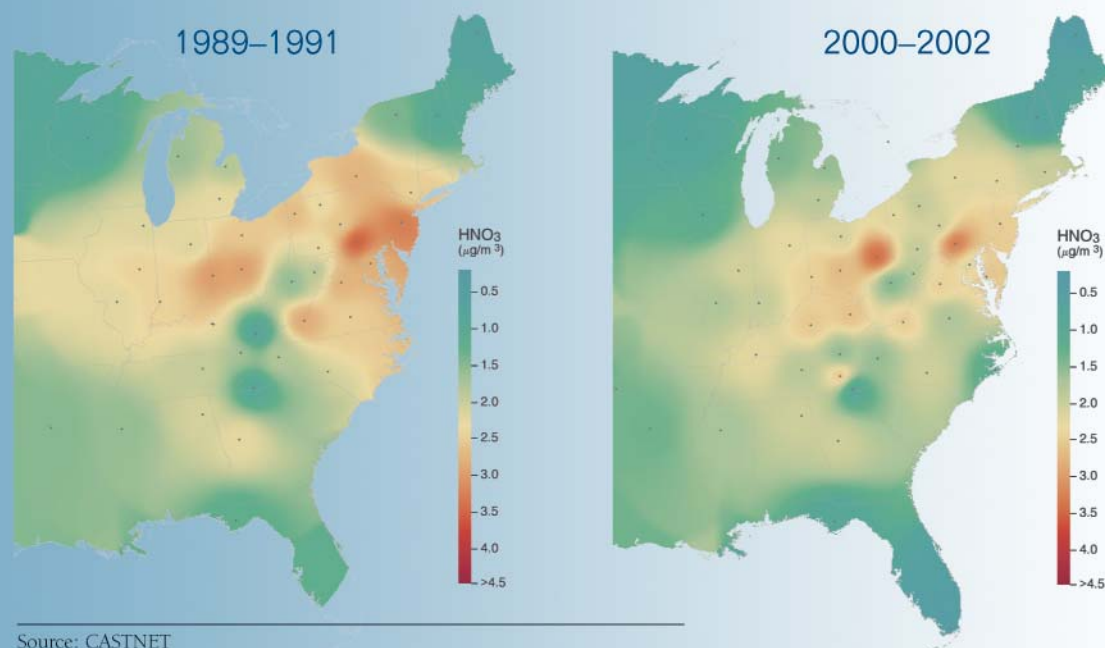
In contrast, the only statistically significant published results seem to suggest nitric acid is increasing over time, particularly in the Northeast.¹⁹ Any increase in airborne nitric

FIGURE 17. Comparison of annual ambient sulfate (SO₄²⁻) concentrations in the rural eastern United States

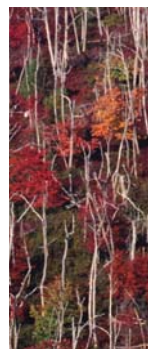


Source: CASTNET

FIGURE 18. Comparison of annual ambient nitric acid (HNO_3) concentrations in the rural eastern United States



Source: CASTNET



acid concentrations is of concern because of the potential for corresponding increases in deposition. It is not clear whether the cause is associated with changes in nitrogenous fertilizers, difficulties measuring nitric acid vapor, the length of the record, or some other reason not associated with upwind point-source emission measurements. Scientists continue to monitor concentrations of nitric acid, as well as all the components of atmospheric deposition discussed here, and it is hoped that additional data will clarify the trends in nitric acid concentrations.

Analyses of mean annual total ambient nitrate concentration data have not revealed any statistically significant changes from 1989 through 2002. Although there are some indications that ambient nitrate concentrations are increasing, particularly in the Midwest, nitrate changes at individual CASTNET monitoring stations have been minimal over this period (see Figure 19). The highest nitrate concentrations in the East were recorded in Illinois, Wisconsin, and Iowa ($>4 \mu\text{g}/\text{m}^3$). Ambient ammonia (NH_3) concentrations,

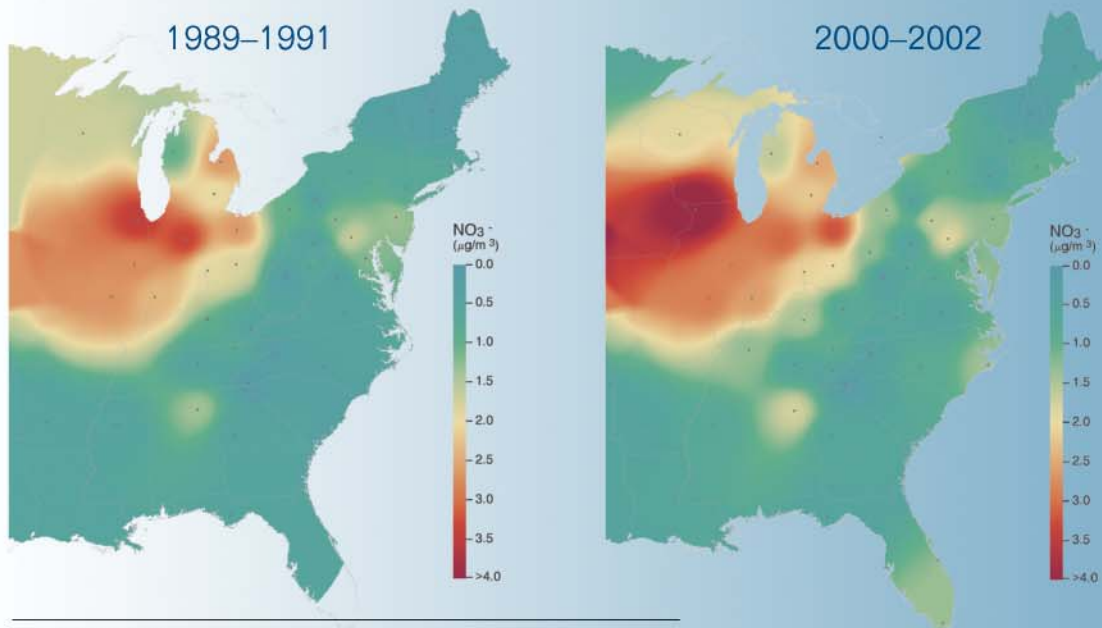
which might also indicate changes in emissions in states with significant agricultural activity, are not routinely measured by either CASTNET or AIRMoN.

Ambient airborne concentrations of ammonium (NH_4) are typically associated with nitrate and sulfate compounds. The highest annual mean ammonium concentrations have been observed in the Midwest and in northern Alabama. Between 1989 and 2002, decreases in ammonium concentrations in the atmosphere were observed in some parts of the U.S. (see Figure 20). The largest decreases of approximately $0.5 \mu\text{g}/\text{m}^3$ were noted in the Midwest. The decrease in ambient ammonium concentrations between 1989–1991 and 2000–2002 appears to be associated with reductions in ambient levels of sulfate which bind to ammonium to form ammonium sulfate. Agricultural ammonia emission themselves have not decreased over the same time period. In fact, ammonia emissions from crops and livestock have increased 14% between 1990 and 2001.²⁰

ACID DEPOSITION: SULFUR IN PRECIPITATION

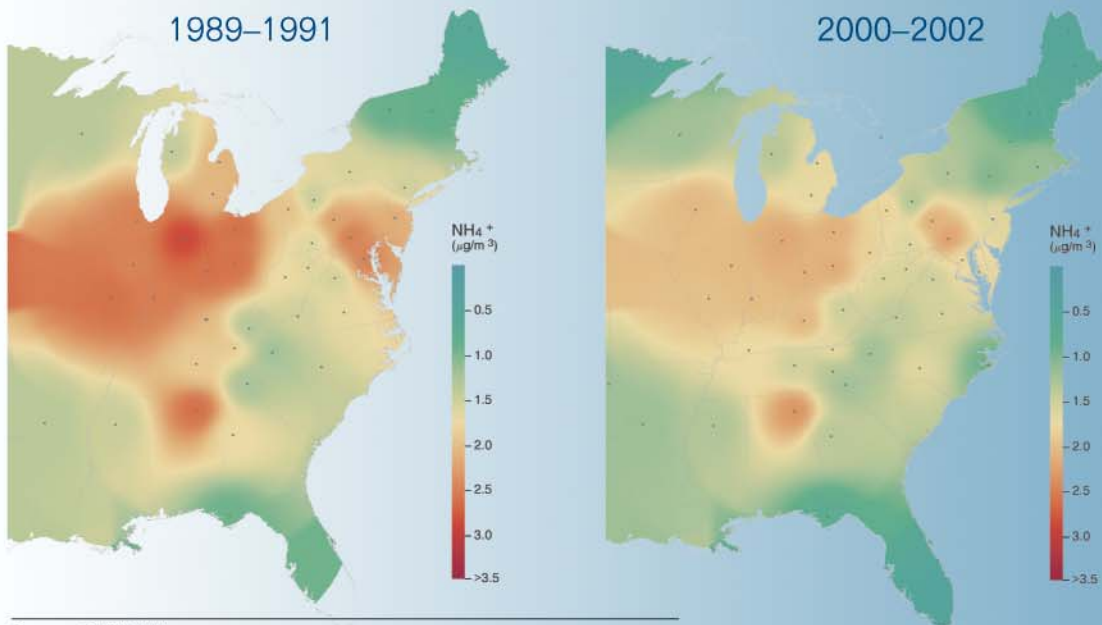
Scientists have documented that both wet and dry sulfur deposition (and the acidity associated with sulfur deposition) have declined with reductions of SO_2 emissions over a large portion of the Eastern U.S. following implementation of Title IV.^{21–25} Strong correlations, near linear, between large scale SO_2 emission reductions and large reductions in

FIGURE 19. Comparison of annual ambient nitrate (NO_3^-) concentrations in rural eastern United States



Source: CASTNET

FIGURE 20. Comparison of annual ambient ammonium (NH_4^+) concentrations in rural eastern United States



Source: CASTNET

sulfate concentrations in precipitation have been noted for the Northeast, one of the areas most affected by acid deposition.²²

A main reason for reduced concentrations of sulfate in precipitation in the Northeast is a reduction in the long-range transport of sulfate from emission sources located in the Ohio River Valley. The reductions in sulfate documented in the Northeast, particularly across New England and portions of New York State, were also affected by SO₂ emission reductions in eastern Canada. Concurrent with these sulfate reductions were similar reductions in precipitation acidity, expressed as H⁺ concentrations. However, acidity may not have decreased as dramatically as sulfate concentrations due to a simultaneous decline in acid-neutralizing base cations which act to buffer acidity. Other factors influencing the decline of sulfate in precipitation may include climate variability (i.e., wet and dry summers) or temporal changes in base cations and ammonium concentrations.²²

Some of the greatest reductions in wet sulfate deposition occurred in the mid-Appalachian region, including Maryland, New York, West Virginia, Virginia, and most of Pennsylvania (see Figure 21). Wet sulfate deposition decreased 40% in the Northeast and 35% in the Midwest and mid-Atlantic since the early 1990s. Reductions of 25% have occurred in the Southeast.

Figure 22 shows the total (wet plus dry) change in sulfur deposition in the conterminous U.S. between 1989–1991 and 2000–2002. Total sulfur deposition is defined as the sum of the dry components (SO₂ and particulate sulfate) and wet components (sulfate in precipitation) as sulfur. Wet sulfate and SO₂ are the largest components of total sulfur deposition. In general, dry deposition is a larger percentage of total deposition in those areas nearest to SO₂ emission sources. The highest rates of total sulfur deposition have been observed in the areas containing the highest SO₂ emissions—the Midwest and the East. Most areas where total sulfur deposition has been calculated have had reductions in total sulfur deposition since 1989–1991.

Baumgardner et al. report that in the early 1990s, the mean annual total sulfur deposition at CASTNET sites in the Ohio River Valley was 15–22 kg/ha. Sites located in Pennsylvania, southern New York, and West Virginia also had total sulfur deposition greater than 15 kg/ha. From 1997–2000, total sulfur deposition ranged from 12–17 kg/ha for sites in the Ohio River Valley. Appreciable decreases in total sulfur deposition of 15–25% have occurred throughout the Eastern U.S. since the early 1990s.²¹

ACID DEPOSITION: NITROGEN IN PRECIPITATION

Nitrate concentrations in precipitation measured at NADP/NTN sites have generally remained the same or increased in some regions (e.g., the Southeast) over the past 15 years. Unlike sulfate concentrations, sharp declines in nitrate concentrations have not been observed in the Northeast, but some decline has occurred.²⁶ While wet nitrate deposition does appear to be substantially lower in the East in 2000–2002 (see Figure 23), nitrate concentrations in precipitation did not change (see Figure 24). Therefore, the lower nitrate deposition in 2000–2002 appears to be related to lower precipitation levels over those same years.

Other researchers have also not found significant reductions in nitrogen deposition since 1990. Lynch, Bowersox, and Grimm found that most areas of the country were not substantially different in reduced or oxidized nitrogen in 1997–1999 compared to historic levels. These findings were not unexpected and are consistent with the NO_x emissions that were not appreciably affected by Title IV in 1996 or 1997 on a broad, regional basis.²⁷ The control of NO_x emissions under Title IV was not required until 1996. Moreover, any decreases in NO_x emissions from power generation have been significantly offset by increases from the vehicle sector from 1991 to 2000.²⁶ In addition, it is interesting to note that while air quality concentrations of ammonium have decreased in the Midwest, both concentrations of ammonium in precipitation and deposition of ammonium have increased in that region since 1985.²⁸

Figure 25 shows the difference in total (wet plus dry) nitrogen deposition in the conterminous U.S. between 1989–1991 and 2000–2002. Total nitrogen deposition is the sum of the dry deposition components (nitric acid, particulate nitrate, particulate ammonium) and wet deposition components (nitrate and ammonium in precipitation). Wet nitrate, wet ammonium, and nitric acid are the largest contributors to nitrogen deposition. As is the case with sulfur, the dry nitrogen components comprise a larger part of total nitrogen deposition in those areas nearest to sources of NO_x emissions. In some areas of southern California, for example, where NO_x emissions are predominantly from mobile sources, the ratio of dry to wet deposition is approximately 4:1.

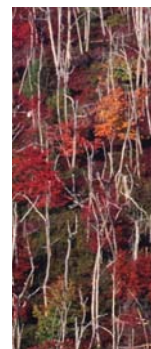
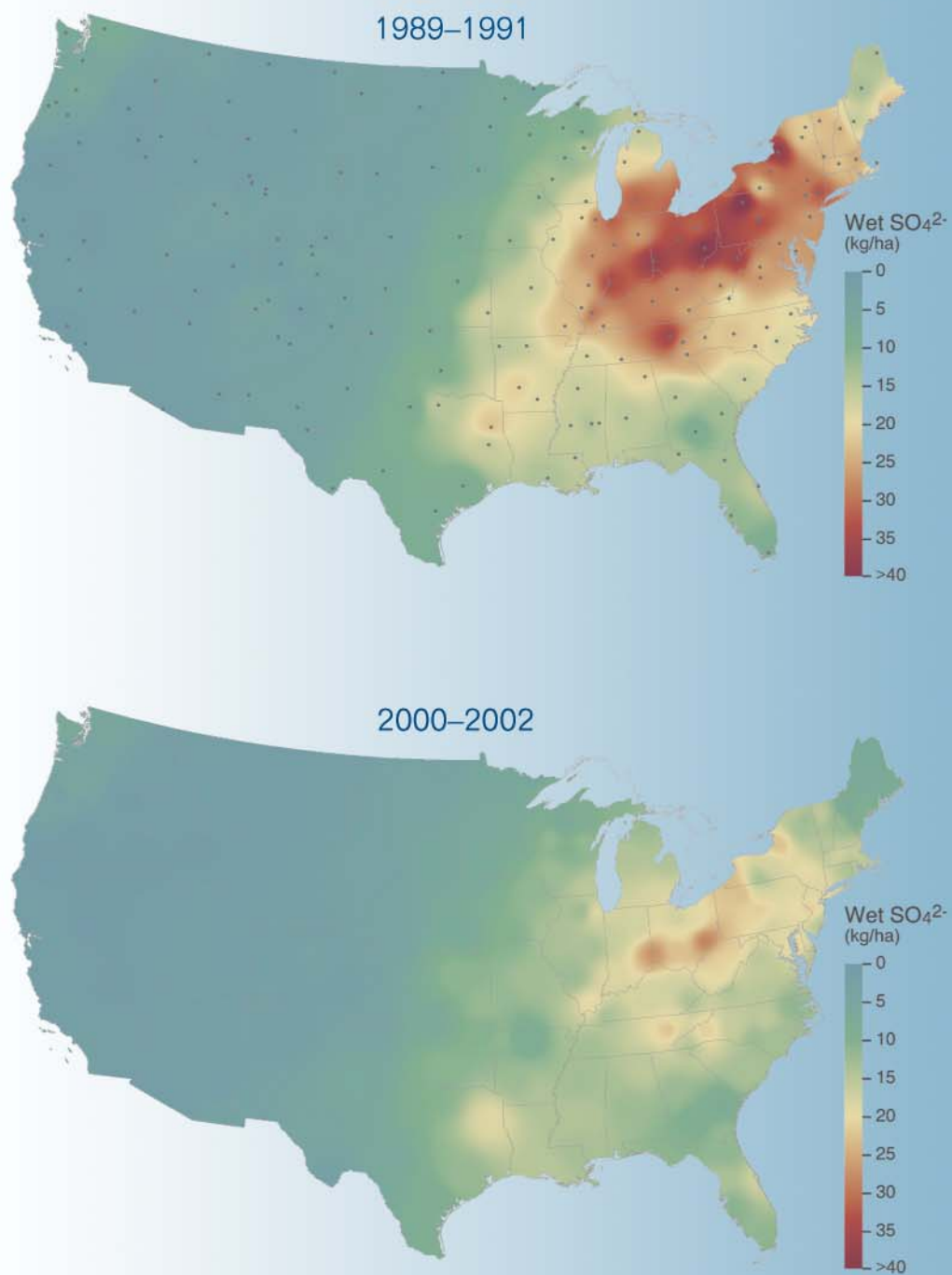


FIGURE 21. Comparison of annual wet sulfate (SO_4^{2-}) deposition in the United States



Source: NADP/NTN

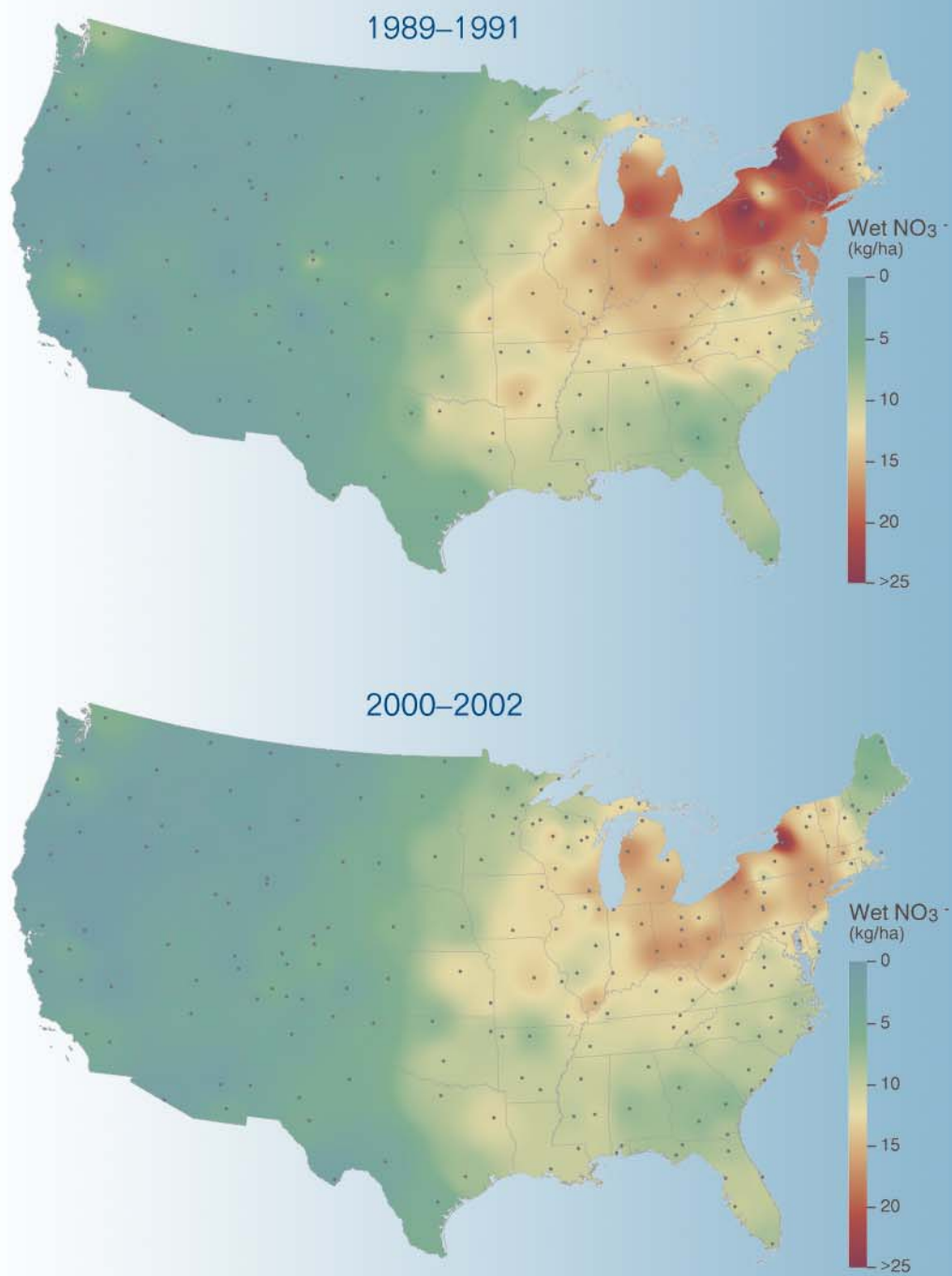
FIGURE 22. Comparison of annual total (wet plus dry) sulfur deposition in the United States



Source: NADP/NTN and CASTNET

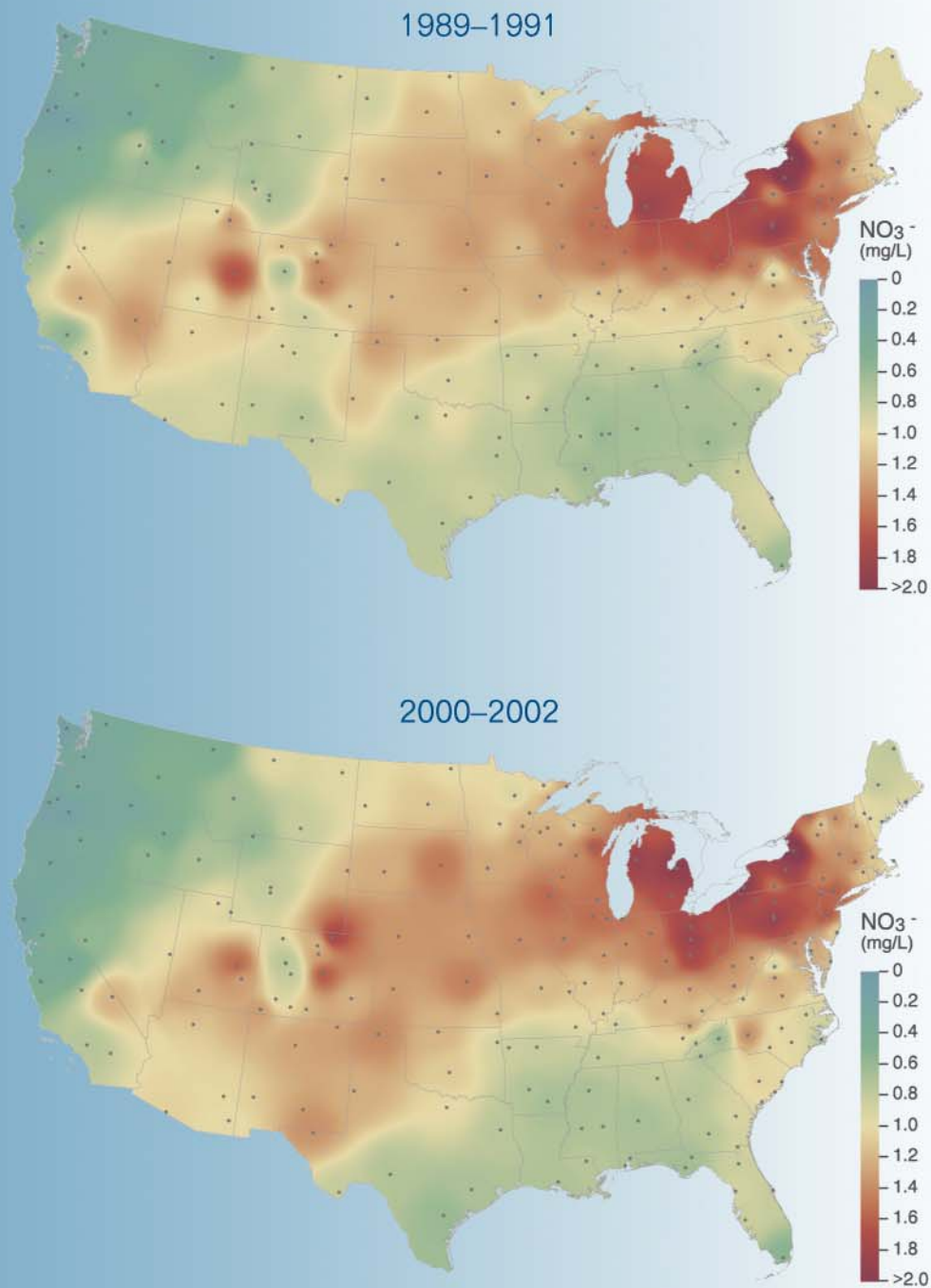


FIGURE 23. Comparison of annual wet nitrate (NO_3^-) deposition in the United States



Source: NADP/NTN

FIGURE 24. Comparison of annual concentrations of nitrate (NO_3^-) in wet deposition in the United States



Source: NADP/NTN



FIGURE 25. Comparison of annual total (wet plus dry) nitrogen deposition in the United States



Source: NADP/CASTNET

Total nitrogen deposition is highest in the Eastern U.S., although several monitoring stations in the West observe high levels of total nitrogen deposition. There are no observable broad-scale reductions in total nitrogen deposition.

Baumgardner et al. report that in the early 1990s, the highest mean annual total nitrogen deposition noted was 8–11 kg/ha in the Midwest and portions of the Northeast. From 1997–2000, little change occurred from the nitrogen deposition values recorded in these areas earlier in the decade.²¹

VISIBILITY

SO₂ and NO_x gases are transformed in the atmosphere into fine particles of sulfates and nitrates. Sulfate and NO₃⁻ particles scatter and absorb light, impairing visibility and contributing to regional haze. Sulfates are generally the largest contributor to visibility impairment in both the East and the West. The visual range under naturally-occurring conditions without pollution in the U.S. is approximately 75–150 km (45–90 miles) in the East and 200–300 km (120–180 miles) in the West.

Data from the IMPROVE network, which monitors visibility trends in national parks, show that visibility has remained virtually unchanged since the early 1990s (see Figure 26). The level of visibility impairment on the worst visibility days in the West is similar to the levels seen on the best visibility days in the East. In 2001, mean visual range for the worst days in the East was only 29 km (18 miles) compared to 117 km (73 miles) for the best visibility. In the West, visibility impairment for the worst days remained relatively unchanged over the 10-year period, with the mean visual range for 2001 (103 km or 63 miles) nearly the same as the 1992 level (98 km or 61 miles). Visibility in the East is still significantly impaired in national parks and wilderness areas, especially on the haziest days.

Ecological Recovery

The atmospheric and environmental response to a reduction in pollutants is a complex and lengthy process.^{29, 30} It takes only a few hours for a reduction in emissions to improve air quality; it takes days to weeks for reductions in deposition to appear. Once the pollutants are deposited on the ecosystem, biogeochemical and hydrologic cycling processes drive the rate of recovery. Previous research tells us that, even after acid deposition decreases, ecosystems can experience lag times of several decades between chemical recovery (e.g., increased pH) and biological recovery (e.g., repopulation of fish or forest regrowth). A short “episodic” period of acidification can be eased in a few weeks to months; recovery from long-term “chronic” acidification can take years or even decades. Some soil processes can recover in a few weeks to months; building up the appropriate soil nutrient reserves can take centuries. Recovery of forest ecosystems generally takes years to decades. Therefore, while some ecological recovery processes occur quickly, others will take place more gradually over a generation or more. Every additional year of monitoring, research, and analysis improves our understanding of these recovery processes and allows us to better predict environmental response to emission reductions.

FRESHWATER ACID-SENSITIVE ECOSYSTEMS

Acid deposition can lead to acidification of surface waters. Acidification and low acid neutralizing capacity (ANC) can, in turn, lead to the loss of sensitive fish populations from those waters³¹ (see Figure 27). In the 1980s, acid rain was found to be the dominant cause of acidification in 75% of acidic lakes and 50% of acidic streams.³¹ Broad areas of the United States still contain large numbers of lakes and streams with little ability to absorb acid deposition (a condition known as low acid neutralizing capacity or ANC). This includes portions of the Northeast (particularly Maine and the Adirondack and Catskill Mountains), the Appalachian Mountains, and areas of the Western United States (see Figure 1). High-elevation watersheds with steep topography, extensive areas of exposed bedrock, deep snowpack accumulation, and shallow, base-poor soils are very sensitive to episodic acidification.³² Such systems are common throughout the mountainous West and in portions of the Northeast and Appalachian Mountains.

Freshwater monitoring in the Eastern United States is conducted by many programs, including the EPA's Temporally Integrated Monitoring of Ecosystems (TIME) and Long-Term Monitoring (LTM) projects that were initiated in the early 1980s by EPA's Office of Research and Development (see Figure 28). The purpose of these networks is to detect

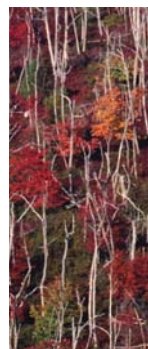
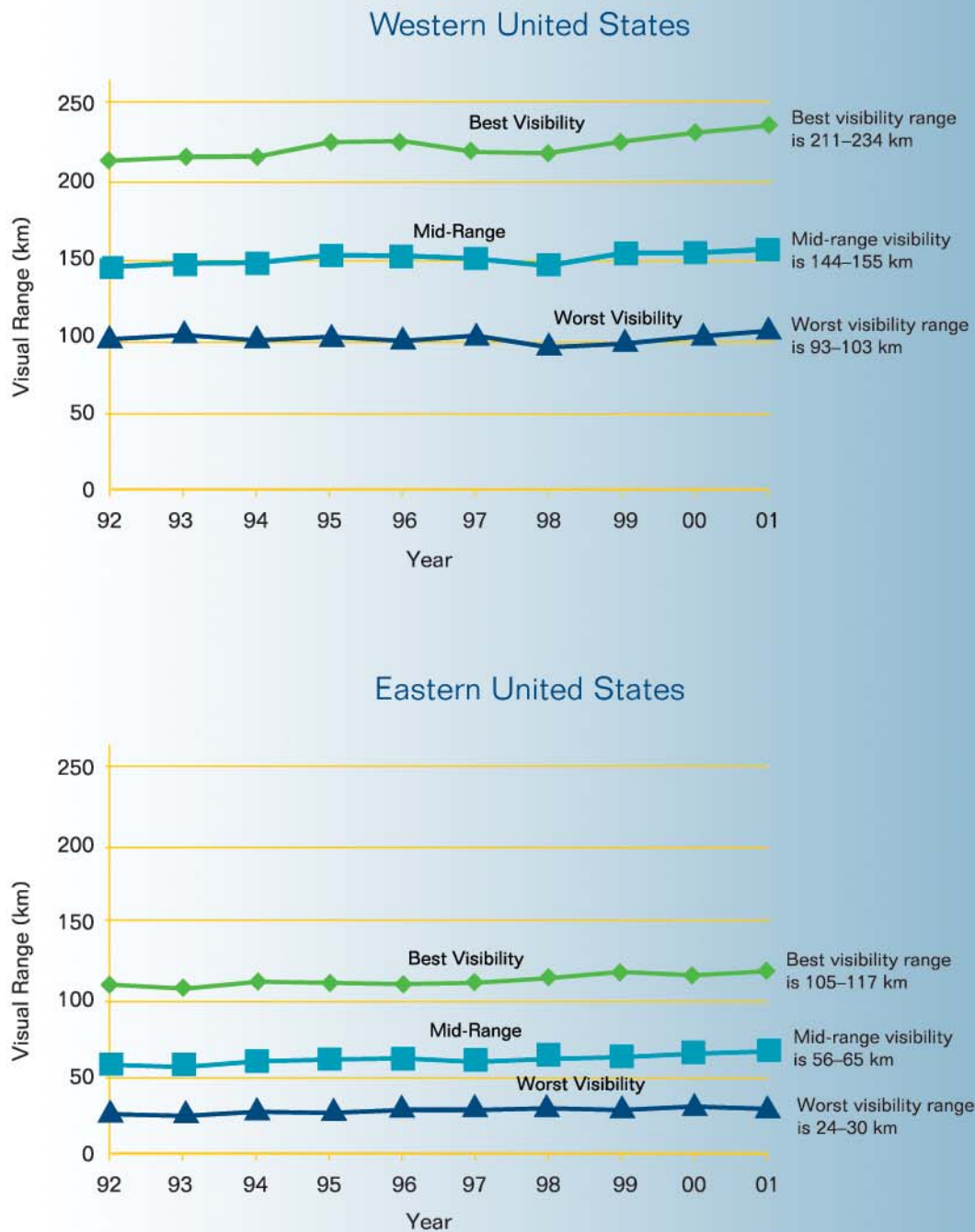


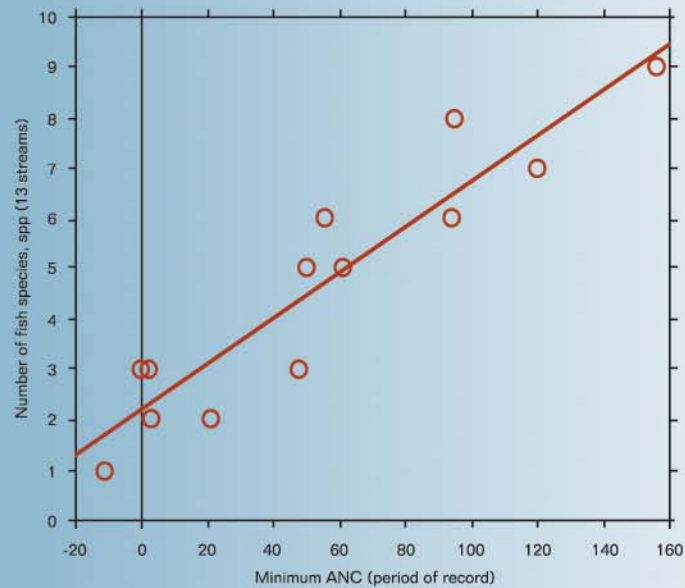
FIGURE 26. Trends in visibility in Class I areas
1992–2001



Note: The 1990 Clean Air Act Amendments identified 156 national parks, wilderness areas, and other federal areas where visibility is highly valued. These areas are known as “mandatory Class I federal areas.”

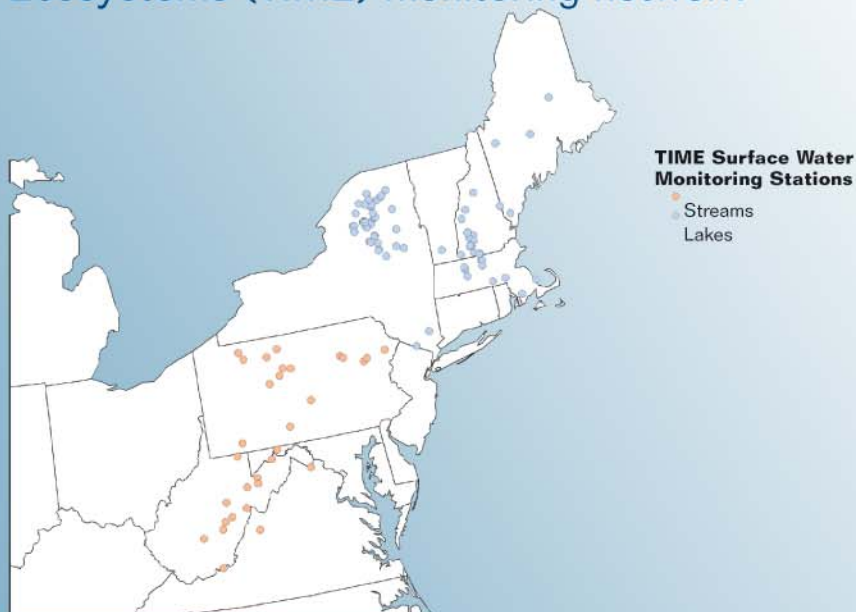
Source: EPA 2002 Trends Brochure

FIGURE 27. Relationship between acid neutralizing capacity (ANC) and the number of species present in aquatic freshwater ecosystems in Shenandoah National Park



Source: Arthur Bulger, University of Virginia

FIGURE 28. Map of the Temporally Integrated Monitoring of Ecosystems (TIME) monitoring network



Source: Stoddard et al., 2003, Response of surface water chemistry to the Clean Air Act Amendments of 1990 (See #36 in References section.)



trends in regional populations of lakes or streams to determine whether emission reductions have had the intended effect of reducing acidification of lakes and streams. TIME/LTM monitors a total of 145 lakes and 147 streams, representing all of the major acid-sensitive regions of the northern and eastern U.S. (upper Midwest, New England, Adirondack and Catskill Mountains, northern Appalachian Plateau, Ridge and Blue Ridge Provinces of Virginia). Additional sites in acid-sensitive regions of the Southeast, Midwest, and West would make more complete assessments possible. TIME/LTM measures a variety of important chemical characteristics, including ANC, pH, sulfate, nitrate, major cations (e.g., calcium and magnesium), and aluminum. While the representativeness of the TIME/LTM network is somewhat limited, the TIME program is the most coherent individual regional dataset for this kind of analysis.

In addition, the U.S. Geological Survey has been measuring surface water quality at several research watersheds throughout the United States, where sample collection during hydrologic events and ancillary data on other watershed characteristics have been used to assess the watershed processes controlling acidification of surface waters.³³⁻³⁵ The NSF Long-Term Ecosystem Research (LTER) watershed at Hubbard Brook, New Hampshire, and university-sponsored watersheds throughout the East are also being monitored for long-term changes in water quality. Like the LTM program, these watersheds were selected to represent specific environmental conditions (alpine lake outlet, streams draining shallow acidic soils, etc.). The TIME program and the broader Environmental Monitoring and Assessment Program (EMAP) are the primary programs that provide probability-based data on surface water quality, and thus can be used to provide regional estimates of acidification recovery at base flow conditions. The current advantage of the TIME and LTM programs is that the data reside in a common database and common methodologies have been applied to all samples.

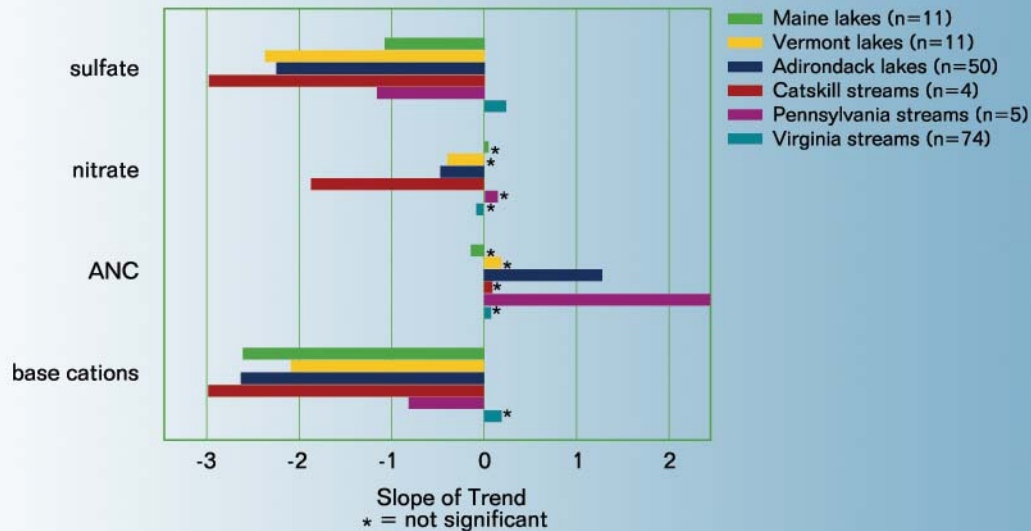
A recent report using this TIME/LTM data concludes that measurable improvements in surface water chemistry (lower sulfate concentrations and decreases in acidity) have resulted from emissions regulations promulgated pursuant to the 1990 CAAA, primarily under the Acid Rain Program.³⁶ This conclusion was reached while acknowledging that other changes, including climate variability, forest maturation and recovery from disturbances, and land use history are also contributing to changes in the chemistry of lakes and streams in the Eastern United States. A summary of the TIME/LTM data is presented in Figure 29. A prediction of the long term response of lakes and streams to reductions in acid deposition is provided in Chapter 4.

In three of the five areas studied by Stoddard et al.³⁶ one-quarter to one-third of lakes and streams previously affected by acid rain are no longer acidic at base flow conditions, although they are still highly sensitive to future changes in deposition. In other areas, signs of recovery are not yet evident, suggesting that additional reductions are necessary for further ecosystem recovery. In general, trends in nitrate concentrations were much smaller than trends in sulfate concentrations, though lakes in the Adirondacks and streams in the northern Appalachian Plateau exhibited significant downward trends in nitrate in the 1990s. It should be noted however, that nitrate increased during the 1980s and decreased dramatically in 1992 for reasons unrelated to changes in deposition. Analysis of stream nitrate concentrations based on the 20-year record indicates no significant or slightly decreasing trends.³⁷ Increasing ANC, an indicator of aquatic ecosystem recovery, was evident in three of the regions (Adirondacks, northern Appalachian Plateau and upper Midwest) and was unchanged in New England and the Ridge/Blue Ridge region. Modest increases in ANC have reduced the number of acidic lakes and stream segments in some regions:

- Eight percent of lakes in the Adirondacks are acidic, down from 13% in the early 1990s.
- In New England, 5.5% of lakes are acidic, an insignificant change from the early 1990s when 5.6% of lakes in the region were acidic.
- Fewer than 1% of lakes in the upper Midwest are acidic, down from 3% in the early 1980s.
- Eight percent of the stream length in the northern Appalachian Plateau region is currently acidic during base-flow conditions, down from 12% in the early 1990s.
- There has been no change in the number of acidic waters in the Ridge/Blue Ridge region in the past decade.



FIGURE 29. Trend in acidification of eastern lakes and streams 1990-2000



Note: Decreasing values for sulfate and nitrate indicate reductions in acidity; increasing values for ANC indicate recovery of the capacity to buffer acid deposition without becoming acidic. Decreasing values for base cations can balance out decreasing sulfate and nitrate values, preventing ANC from increasing and leaving waters vulnerable to acidification.

Source: Stoddard et al., 2003. Response of surface water chemistry to the Clean Air Act Amendments of 1990 (See #36 in References section.)



Lake and stream recovery is due to reductions in acidic deposition, primarily sulfate deposition, achieved by Title IV.³⁶ There have been decreases in sulfate concentrations in almost all Adirondack lakes that coincide with reductions in atmospheric concentrations of sulfur.³⁸ These reductions in sulfate, as well as reductions in nitrate concentrations that do not appear to be due to changes in atmospheric deposition, have resulted in increased pH and ANC as well as reductions in the amount of toxic inorganic aluminum in these lakes.³⁸ In spite of declining sulfate concentrations, however, TIME/LTM data show that some lakes and streams have not begun to recover.

Recovery was not evident in New England or in the Ridge and Blue Ridge Provinces (Virginia); the latter region is not expected to recover immediately, due to the nature of forest soils in the province. In part, declining levels of base cations (calcium, magnesium, and potassium) in lakes and streams throughout the East are believed to delay

the onset of recovery.³⁶ In addition, it should be noted that, although chemical recovery (i.e., an increase in ANC and decrease in sulfate and nitrate concentrations) has begun in some lakes and streams, full biological recovery of fish and other aquatic organisms takes significantly longer.³⁰

Throughout the Appalachians, many waterbodies are still acidic enough to damage sensitive fish and aquatic life. In Virginia, for example, over a decade of quarterly stream monitoring shows that the predominant trend, as indicated by declining ANC, has been continued acidification. The number of chronically acidic Virginia trout streams has increased, while the number of transitional and not-acidic streams has declined.³⁹ The consequences for individual species have been well documented in the Shenandoah National Park by the Fish in Sensitive Habitats (FISH) Project. The FISH project demonstrated that acid-sensitive fish in both chronically and episodically acidic streams in Shenandoah National Park have lower body size and weight, both indications of chronic stress.

Some lakes in the Colorado Front Range are showing indications of being affected by higher atmospheric nitrogen loads from urban, agricultural, and industrial sources.⁴⁰ In the central and northern Rockies, sediment record studies strongly suggest that lakes began responding to nitrogen



deposition levels in the region as early as the 1950s.^{40, 41} Recent analyses demonstrate regional differences in lake surface water chemistry and show evidence of ecological change in the region. For example, studies of high-elevation lakes in the central Rockies found significantly higher nitrate concentrations in lakes on the east side of the Front Range, where emission sources are numerous, as compared to lakes on the west side.^{40, 42} An intensive sampling study projected that at least two sites in the Green Lakes Valley in the Colorado Front Range could become chronically acidic within the next decade, and a third site could become episodically acidified at present rates of ANC decrease.⁴² It has also been demonstrated that algal communities, soils, and subalpine forests on the east side of the Front Range are beginning to show signs consistent with receiving more nitrogen deposition from fixed, mobile, and agricultural nitrogen sources.⁴⁰ With the accumulating weight of evidence, some researchers conclude that high-altitude watersheds in the Colorado Front Range show symptoms of nitrogen saturation.^{43, 44}

In some forest ecosystems, particularly in the Northeast, sulfur and nitrogen have accumulated so much that the soils are unable to retain them. This leads to leaching of important nutrients and higher nitrate and sulfate concentrations in some surface waters. The release of decades worth of previously accumulated atmospheric deposition may delay the recovery of these surface waters in response to emission reductions.³⁰ Recovery of acidified waters is also slowed by continuing acid deposition, the presence of nitrate in surface waters, the contribution of naturally occurring acid sources, and the number of physical, chemical, and biological changes needed in the ecosystem before it can function as an ecosystem unaffected by acid deposition. Nitrogen export from recovering streams in the Catskill Mountains was reported to be greater during warm years than cool years, suggesting that a warmer climate could enhance acidification of surface waters if nitrogen deposition rates remained the same.³⁷

Throughout the United States, most streams and drainage lakes experience some decline in ANC during heavy rainstorms, snowmelt, or other episodic events. Current programs for monitoring trends in surface water chemistry either specifically avoid hydrologic 'episodes' (high flows during rain events or snowmelt) or sample with a set periodicity that ultimately samples random flow conditions. The trends presented are therefore representative of baseflow or median flow conditions over time and do not indicate trends in surface-water chemistry during high-runoff periods. In the Northeast and mid-Atlantic regions of the United States, the number of lakes and streams that experience episodic acidification are estimated to be much greater than the number of chronically acidic waterbodies.⁴⁵

Episodic acidification has been reported in the mid-Atlantic and Northeastern region in areas such as the Ridge and Valley Province of Pennsylvania, Virginia, and Maryland, the northern Appalachian Plateau of Pennsylvania, the Catskill and Adirondack Mountains of New York, and the Atlantic Coastal Plain of Maryland.⁴⁵ Several recent studies also have demonstrated episodic acidification of streams in Shenandoah and Great Smoky Mountains National Parks.⁴⁶⁻⁴⁹ A recent study of brook trout streams in Virginia estimated that 24% experience regular episodic acidification at levels harmful to brook trout and other aquatic species.⁴⁶ Due to the difficulties and expense associated with collecting water samples during episodes of acidification, limited data on episodic acidification have been published since the 1988-1990 sampling, and few data collected after 1994 have been published. As a result, it is unknown whether the regional incidence of episodic acidification has decreased as a response to declines in acidic deposition in the 1990s.

FOREST ECOSYSTEMS

Acid deposition especially combined with other pollutants and natural stresses, can also damage forest ecosystems. Sulfates and nitrates from acid deposition leach nutrient base cations (calcium, magnesium, and potassium) from tree needles and leaves and from forest soils, reducing the forest's capacity to buffer further acidification and removing elements essential for tree growth. Acidification also leads to the mobilization of naturally-occurring aluminum, which may interfere with nutrient uptake by roots in forest soils. In addition, exposure to tropospheric ozone (a product of NO_x emissions interacting with volatile organic carbons (VOCs)) has both acute toxic effects on plant leaves and chronic toxic effects on the entire plant. The combined effects of depletion of foliar and soil nutrients, mobilization of aluminum and exposure to ozone make trees more susceptible to drought, temperature extremes, and diseases.⁵⁰ Several forests throughout the U.S. are beginning to show signs of nitrogen saturation, a condition where the inputs of nitrogen exceed the forest's need for them and

excess nitrogen is leached into surrounding waterways.⁵¹ There are as yet no forests in the U.S. where research indicates recovery from acid deposition is occurring, as indicated by reversal of the soil acidification such as net accumulation of base cations and reductions in aluminum concentrations.

There is no broad-scale assessment of forest health the way there has been for freshwater lakes and streams. However, both a series of individual studies in a variety of locations in areas sensitive to acidic deposition and regional studies across a gradient provide a snapshot of the status and trends in forest ecosystems. For example, mortality of red spruce in the mountains of the Northeast has increased, due in part to exposure to acidic cloudwater.²⁹ Acid deposition has led to reduced growth and/or vitality of red spruce across the high elevation portion of its range, thereby increasing the trees' sensitivity to cold weather injuries and eventually resulting in a high rate of mortality.⁵²

Forest soils are also adversely affected by acid deposition. Studies in New Hampshire,^{53, 54} the Catskill Mountains in New York,⁵⁵ the Adirondacks in New York, West Virginia,⁵⁶ North Carolina,⁵⁷ South Carolina,⁵⁸ Tennessee,⁵⁹ and Ontario, Canada,⁶⁰ have documented nutrient base cation (e.g. calcium, magnesium, potassium, and others) depletion in soils due to acid deposition and forest regrowth. Resampling of forest soils in northwestern Pennsylvania originally sampled in the 1960s shows an increase in soil acidity.⁶¹ In contrast to these studies,⁶² at one site in New Hampshire, Hamburg et al.,⁶³ inferred (not direct re-measurement) no decline in calcium in the forest floor in a chronosequence study in New Hampshire. At sites where there may be appreciable amounts of dolomitic parent material⁶⁴ that are accessible to trees, soil calcium may not be depleted to the extent it can be in nearby soils that lack a dolomitic source.⁵⁹

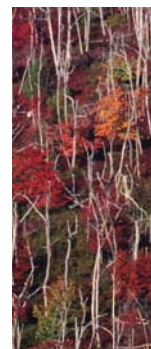
In these and other examples of calcium depletion in forest soils in Europe,^{65, 66} it has not been possible to quantify the component of depletion attributable to anthropogenic acidic deposition versus tree uptake.

Similarly, in reported instances of forest decline it has not been possible to attribute the decline to calcium depletion directly. However, calcium depletion has been implicated indirectly in the decline in sugar maple in the U.S. and Canada⁶⁵, and calcium depletion adversely affects many aspects of tree physiology and forest ecosystem health.^{67, 68}

The potential for weathering re-supply of exchangeable soil calcium remains an important uncertainty because estimates of weathering are based on indirect estimates.⁶⁹ Soil acidification may increase the rate of weathering, but the incremental increase in calcium release is likely to be small in soils that are already acidic. Studies that have attempted to quantify calcium weathering rates in acidic forest soils in the Eastern U.S. generally have found that rates are low^{53, 54, 70-72} in comparison with typical combined rates of tree uptake and soil leaching.⁶⁹

Acid deposition has also contributed to a regional decline in the availability of soil calcium and other base cations in many different types of forest ecosystems. In the high elevation and mid-elevation spruce-fir forests of New York, New England, and the southern Appalachians, the change in soil nutrient ratios (lower calcium/higher aluminum) can disrupt physiological processes that are important to maintaining forest health. These changes lower resistance to natural stresses, such as insects, disease and climatic extremes.^{67, 68} Acid deposition is also contributing to the depletion of base cations in many poorly buffered soils supporting southern pines. While this may slightly bolster growth of southern pines in the short-term, it is expected to have adverse effects on productivity over the long-term. Finally, the high mortality rates and reduced vigor reported for sugar maples experienced in northern Pennsylvania and Quebec, Canada over the last decade may be attributed in part to cation depletion from those soils.⁷³⁻⁷⁷

Whereas the vast majority of forest ecosystems in the Western U.S. do not appear to be significantly affected by acid deposition, certain ecosystems in southern California and the Colorado Front Range are negatively affected, especially by high rates of nitrogen deposition. Nitrogen deposition in most affected areas of the Colorado Front Range, southern California, and in the Sierra Nevada is generally from a mix of mobile, industrial, and agricultural emissions sources.⁷⁸ In some cases, ozone (formed from NO_x emissions and other precursors) is also causing damage. Many of these sites are showing signs of nitrogen saturation. Nitrogen saturation occurs when the supply of nitrogen from deposition exceeds the nutritional demands of the ecosystem and nitrogen is gradually released or leached from the watershed into the surface waters as nitrate.⁷⁹ In the Colorado Front Range, responses to chronic nitrogen deposition are evident in changes in the chemical



composition of pine needles and soils. These results are interpreted as subtle signs of the effects of nitrogen deposition, suggesting that the trajectory towards nitrogen saturation may be in the incipient stages.⁴⁰ Additional studies along air pollution gradients demonstrate that forest and chaparral sites in southern California and alpine ecosystems of the Front Range in Colorado are showing signs of nitrogen saturation.^{43, 80} The sites most affected are near intensive livestock operations and high population centers, although extremely high streamwater nitrate concentrations have been reported from a low-elevation chaparral watershed in Sequoia National Park in the Sierra Nevada Mountains in central California.⁸¹

While forest ecosystems are clearly still suffering significant damage from acid deposition, the reduction in acid deposition due to Title IV is expected to be beneficial to these forest ecosystems in the long-term. Forests are generally thought to recover more slowly than aquatic ecosystems because of the complex series of processes that must take place. Leached nutrients must be restored through weathering of the bedrock or atmospheric deposition, and soilwater aluminum concentrations must be reduced. Even after soil chemistry is restored, recovery of sensitive forests is not expected to occur for decades because of the extensive recovery time of trees.

COASTAL ECOSYSTEMS

The nitrogen component of acid deposition is a significant source of nitrogen to many estuaries and coastal waters in the Eastern U.S. Excessive nitrogen loads from a variety of sources, including atmospheric deposition and runoff from agricultural practices, cause many of these estuaries and coastal waters to periodically become eutrophic.⁸² Eutrophic conditions include algal blooms (some of which may be harmful), low levels of dissolved oxygen in the water (hypoxia or anoxia) which can stress or kill fish and shellfish, and changes in the ecological structure of the ecosystem. There are currently 44 estuaries in the U.S. that are considered highly eutrophic, 37 of which are on the eastern or gulf coasts. Many of these are expected to become more eutrophic—to have worsening symptoms, including more algal blooms and fish kills—in the future.⁸³ Title IV has reduced nitrogen deposition in some coastal areas compared to what it would have been without Title IV (see Figures 23 and 25). However, in many sensitive coastal watersheds there has been little or no reduction in nitrogen deposition since 1990.

Materials and Structures

There is no monitoring network in place to assess the effects of reductions in acid deposition on materials and structures. However, based on our understanding of the

processes involved, it is possible to predict likely changes that will take place.

SO₂, NO_x, and many of the pollutants they form corrode materials, particularly those made of limestone or marble. Monuments and historic buildings, outdoor structures such as bridges and buildings, and automotive paints and finishes are all susceptible to damage by acidic pollutants. One set of studies indicated that several air pollutants from coal combustion are the main sources of soiling on a limestone building in Pittsburgh, Pennsylvania followed by erosion due to rainfall.⁸⁴⁻⁸⁶ In general, most damage from air pollutants appears to come from dry deposition. The rate of dry deposition is often accelerated when the surface is wet, so that structures affected by dewfall are expected to be especially vulnerable. Rain wets exposed structures, again modifying the dry deposition rates that would be expected if the same structures were dry. Hence, there is a strong interplay among dry deposition, wet deposition, and surface wetness that serves to complicate the understanding of causes of damage in specific locations.⁸⁷ In addition, in rural areas and in areas where buildings and monuments remain wet for long periods of time, wet deposition can be a significant or primary cause of damage.^{88, 89}

Weathering due to acid deposition often harms cultural assets (e.g., statues and monuments) more than purely operational resources (e.g., bridges and buildings). This is because the appearance of cultural resources, where much of their value lies, is particularly vulnerable to damage. There are also historic and emotional values attached to cultural assets, which increase the value of their preservation. Title IV has reduced the risk of damage to sensitive buildings and materials by reducing the amount of SO₂ and NO_x emitted into the atmosphere and the amount of dry sulfur deposition reaching sensitive structures. Therefore, ongoing monetary costs and cultural losses due to acid gases, particles, and deposition are also expected to be declining under Title IV.



Chapter 3: Assessing Acid Deposition: Advances in the State of the Science

NAPAP has a long history of conducting research related to acid deposition. Throughout the 1980s NAPAP supported a large number of research projects that confirmed the link between SO₂ and NO_x emissions and acidic lakes and streams hundreds of miles away. Recent research is confirming the tight link between emissions of SO₂ and the amount of several different forms of sulfur in the atmosphere and in precipitation, and improving our ability to measure acid deposition. Research has continued since 1990, albeit on a smaller scale, to increase our understanding of how acid deposition affects trees, soils, lakes, streams, coastal waters, and building materials such as stone and copper. Some of the areas where the most research has been done include: the importance of calcium in mediating soil and forest response to acidification; the role of nitrogen in acidification and recovery from acidification; and the role of nitrogen deposition in coastal ecosystems. In addition, substantial advances have been made in understanding the human health impacts of fine particles, including sulfates and nitrates, which are briefly mentioned here.

Air Quality, Deposition, and Visibility

Reductions of SO₂ emissions from power generation under Title IV have resulted in significant declining trends in airborne concentrations of SO₂ and sulfate throughout the Eastern U.S. Scientists have determined that the reduction in SO₂ emissions has led to a comparable decrease in SO₂ air concentrations, indicating that the relation-

ship between emissions and air concentrations for SO₂ is close to 1:1. For example, in the Midwest, which experienced some of the highest emission levels and the greatest annual change in SO₂ emissions since 1990, the approximately 35% regional reduction of SO₂ air concentrations corresponds well to the approximately 35% national reduction in SO₂ emissions. Reductions in ambient airborne sulfate concentrations in the Midwest were not as linear; ambient sulfate concentrations declined by only 26%.⁹⁰ The relationship between SO₂ emission reductions and ambient sulfate concentrations is influenced by a number of chemical and meteorological factors that contribute to the non-linear response between emission reductions and downwind concentrations.²³

Scientists have also recently documented that both wet and dry components of sulfur deposition (and the acidity associated with sulfur deposition) have declined in a near linear fashion with the decline in SO₂ emissions impacting the Eastern U.S.²²⁻²⁵ Strong correlations between large-scale SO₂ emission reductions and large reductions in sulfate concentrations in precipitation have been noted for the Northeast—one of the areas most affected by acid deposition.²² A main reason for reduced sulfate concentrations in precipitation in the Northeast is a reduction in the long-range transport of sulfate from emission sources located in the Ohio River Valley. The reductions in sulfate documented in the Northeast, particularly across New England and portions of New York State, were also affected by SO₂ emission reductions in eastern Canada. Factors influencing the decline of hydrogen ions (H⁺) in precipitation may include climate variability (i.e., wet or dry summers) or temporal changes in base cations and ammonium concentrations.²² Concurrent with these sulfate reductions were similar reductions in precipitation acidity, expressed as H⁺ concentrations. However, acidity may not have decreased as dramatically as sulfate concentrations due to a simultaneous decline in deposition of acid-neutralizing base cations that act to buffer acidity.

Emissions of NO_x are transformed in the atmosphere into a series of pollutants, including nitric acid and nitrates. Nitric acid reacts with ammonia and primary particles such as sea spray, soil, and soot to form particle phase ammonium nitrate. From the perspective of acid deposition, nitric acid



is an acidifying gas and a key chemical species for which the dry deposition monitoring networks now have an extensive record. While data from the monitoring networks provide strong evidence of statistically significant declining trends in the concentrations of sulfur species, trends in nitrogen concentrations have not been as pronounced over the past decade.

Scientists are confident that the causes of acid rain and the response of deposition to reductions in emissions are well understood. Most of the recent advances in acid deposition research and monitoring, therefore, are related to improving the quality of data collected by the monitoring networks and developing new statistical methods of analyzing all existing data to better document any environmental change.

Although several direct approaches to measuring dry deposition have been developed and applied over the past decade, inferential models that calculate dry deposition from atmospheric concentrations and other information have been the only practical way to quantify seasonal and annual dry deposition rates of acidic pollutants on the scale needed to operate a nationwide network.⁹¹ CASTNET and AIRMoN-Dry use this approach, which requires local measurements of ambient pollutant concentrations, observations of surface conditions, and standard surface meteorological conditions.⁹² Both these networks use the Multi-layer Model (MLM) to model air pollutant deposition velocity, a key component of dry deposition measurements. Scientists are working to improve the MLM and its effectiveness over a range of vegetation types and weather conditions. Research into deposition velocity modeling has led to innovations that will enable the development of a more accurate, next-generation model.⁹³ The Canadian Air and Precipitation Monitoring Network (CAPMON) and the European Monitoring and Evaluation Program (EMEP) have been able to “scale up” this approach from site-specific estimates to broader landscapes or regions.

The air quality measurements required for using these inferential models are also being improved. Simultaneous sampling using colocated filter packs and duplicate annular denuder systems (ADS), revealed similar precision estimates for most of the measured species between the two approaches.⁹⁴ Comparisons of weekly ADS results and composite weekly filter pack results generally show good agreement for sulfate and total nitrates. However, in some instances, filter pack nitric acid determinations may be biased high when substantial photochemical reactivity in the atmosphere is documented and filter packs may underestimate SO₂ results by 12% to 20%. While perhaps significant, this amount of bias is not expected to substantially change the trend analyses in the Report.

Researchers are also working to improve methods of measuring actual dry deposition that can provide higher quality data. Surface wash techniques such as throughfall (precipitation collected after it has passed through the tree canopy) and stemfall (also called stemflow; the process whereby precipitation drips down the branches and trunk of a tree or other rooted plant) that measure deposition quantities and chemical compositions are considered more reliable, especially for sulfur in complex mountainous terrain or locations where patchy forest conditions exist.^{95, 96} Although throughfall is not a widely used technique for routine atmospheric deposition monitoring, it is being evaluated by national dry deposition networks as an inexpensive method that produces high quality data representative of an area beyond a single point for a long period of time. At a minimum, throughfall is a cost-effective way to enhance inferential modeling results with actual field measurements.

In recognition of the need to quantify total deposition rates across natural landscapes of mixed vegetation, sometimes in complex terrain, there is need to build upon the developments made in several other programs in EPA and in other agencies. For example, the aircraft flux systems developed within the NOAA AIRMoN program to address this issue offer a new opportunity to determine how surface complexity influences dry deposition rates. Moreover, the bounding techniques developed in the acid rain decade of the 1980s require new attention and verification, possibly using throughfall methods as well as micrometeorological models.

The NADP/NTN, the largest wet deposition monitoring network in the U.S., is seeking new technologies to incorporate into their sample collection protocols to further improve the accuracy of the wet deposition monitoring. Improving wet deposition monitoring methods entails advancing sample collection techniques, the methods used for evaluating the data generated and the approaches for estimating site-specific and regional trends.

A large amount of the research in the wet deposition field has involved developing new



ways to analyze the monitoring data. To determine whether emission reductions have had their intended effect of reducing wet deposition, measurement data can be statistically modeled to characterize the magnitude and spatial distribution of reductions in wet deposition. The estimation of long-term trends with statistical models is affected by a number of factors such as the magnitude and shape of the underlying trend to be estimated and the length and variability of the data record. The advantage, however, is in deriving estimates of trend and uncertainty in data that have been adjusted for the sources of variability that may also influence the observed temporal pattern.⁹⁷

Aquatic and Forest Ecosystems

Soils, forests, surface waters, and aquatic biota (e.g., fish and algae) are inextricably linked, sharing water, nutrients, and the other essential building blocks of a successful ecosystem. Therefore, to understand the full effects of acid deposition it is necessary to understand the interactions between all of these systems. For example, sulfur and nitrogen from acid deposition can be retained in watershed soils and released as sulfate and nitrate drainage into lakes and streams even after the levels of acid deposition decrease. The effect of acid deposition on an ecosystem depends largely upon the ecosystem's ability to neutralize the acid.³⁰ This is referred to as an ecosystem's acid neutralizing capacity (ANC).

Acid neutralization occurs when positively charged ions such as calcium, potassium, sodium, and magnesium, collectively known as base cations, are released. As water moves through a watershed, two important chemical processes act to neutralize acids. The first involves cation exchange in soils, a process by which hydrogen ions from the acid deposition displace other cations from the surface of soil particles, releasing these cations to soil and surface water. The second process is mineral weathering, where base cations bound in the mineral structure of rocks are released as the minerals gradually

break down over long time periods. As the base cations are released by weathering, they neutralize acidity and increase the pH level in soil water and surface waters. Acid deposition, because it consists of acid anions (e.g., sulfate, nitrate), leaches some of the accumulated base cation reserves from the soils into drainage waters. The leaching rate of these base cations may accelerate to the point where it significantly exceeds the resupply via weathering and atmospheric deposition.³⁰

FRESHWATER ACID-SENSITIVE ECOSYSTEMS

Acid deposition causes acidification of sensitive surface waters. These waters are sensitive due to their position in the landscape, geomorphology, and/or watershed soils. In the 1980s, acid rain was found to be the dominant cause of acidification in 75% of acidic lakes and 50% of acidic streams.³¹ Areas especially sensitive to acidification include portions of the Northeast (particularly Maine and the Adirondack and Catskill Mountains) and southeastern streams. Some high elevation western lakes, particularly in the Rocky Mountains, have become acidic, especially during snowmelt. However, although many western lakes and streams are sensitive to acidification, they are not subject to continuously high levels of acid deposition and so have not become chronically acidified.³¹ A significant amount of research conducted since 1990 has focused on western acid-sensitive ecosystems.

ANC, a key indicator of the ability of the water and watershed soil to neutralize the acid deposition it receives, depends largely on the watershed's physical characteristics: geology, soils, and size. Waters that are sensitive to acidification tend to be located in small watersheds that have few alkaline minerals and shallow soils. Conversely, watersheds with high ANC tend to contain alkaline minerals, such as limestone. Larger watersheds with well developed riparian zones generally have a greater capacity to neutralize the acids being transported from their headwaters, but large forested watersheds have been shown to acidify during large rainfall and snowmelt episodes.⁹⁸

As acidity increases, aluminum leached from the soil flows into lakes and streams and can be toxic to aquatic species. The lower pH levels and higher aluminum levels that result from acidification make it difficult for some fish and other aquatic species to survive, grow, and reproduce. In some waters, the number of species of fish able to survive has been directly correlated to water acidity. Acidification can also decrease fish population density and individual fish size.³⁰

Recent watershed mass balance studies in the Northeast reveal that loss of sulfate from the watershed exceeds atmospheric sulfur deposition.⁹⁹ This suggests that these



soils have become saturated with sulfur, meaning that the supply of sulfur from deposition exceeds uptake by biotic and abiotic processes in the ecosystem. As a result, sulfur is gradually being released or leached from the watershed into the surface waters as sulfate. Scientists now expect that the release of sulfate that previously accumulated in watersheds will delay the recovery of surface waters in the Northeast that is anticipated in response to the recent SO₂ emission controls.⁹⁹

A recent study at a stream in the Catskill Mountains found that stream nitrate concentrations were positively correlated to mean annual air temperature but not to annual nitrogen deposition.³³ This research suggests that, in soils with large amounts of nitrogen, microbial processes (N mineralization and nitrification), that are sensitive to changes in temperature and moisture, are the primary factors controlling nitrate leaching, rather than atmospheric deposition or vegetation uptake of nitrogen. Therefore, declines in nitrogen deposition in nitrogen-saturated soils may not immediately lead to improvements in streamwater chemistry.³³

A major study of the ecological response to acidification is taking place in the Bear Brook watershed in Maine. Established in 1986 as part of the U.S. Environmental Protection Agency's Watershed Manipulation Project, the project has found that experimental additions of sulfur and nitrogen to the watershed increased the concentrations of both sulfate and nitrate in the West Bear Brook stream. Streamwater concentrations of several other ions, including base cations, aluminum, and ANC changed substantially as well.¹⁰⁰ During the first year of treatment, 94% of the nitrogen added experimentally to the Bear Brook watershed was retained, while the remainder leached into streams as nitrate. Nitrogen retention decreased to about 82% in subsequent years.^{101, 102} Although the forest ecosystem continued to accumulate nitrogen, nitrate leaching into the stream continued at elevated levels throughout the length of the experiment. This nitrate contributed to both episodic and chronic acidification of the stream. This and other similar studies have allowed scientists to quantify acidification processes in eastern watersheds in much more detail than was possible in 1990.

The Appalachian Mountain region receives some of the highest rates of acid deposition in the United States.¹⁰³ The acid-base status of streamwaters in forested upland watersheds in the Appalachian Mountains was extensively investigated in the early 1990s.¹⁰³⁻¹⁰⁶ A more recent assessment of the southern Appalachian region from West Virginia to Alabama identified watersheds that are sensitive to acid deposition using geologic bedrock and the associated buffering capacity of soils to neutralize acid. The assessment found that approximately 59% of all trout

stream length in the region is in areas that are highly vulnerable to acidification and that 27% is in areas that are moderately vulnerable.¹⁰⁷ Another study estimated that 18% of potential brook trout streams in the mid-Appalachian Mountains are too acidic for brook trout survival.¹⁰⁸ Perhaps the most important study of acid-base chemistry of streams in the Appalachian region in recent years has been the Virginia Trout Stream Sensitivity Study.¹⁰⁵ Trend analyses of these streams indicate that few long-term sampling sites are recovering from acidification, most are continuing to acidify, and the continuing acidification is at levels that are biologically significant for brook trout populations.³⁹

During the 1980s and 1990s, an integrated study of atmospheric deposition, terrestrial ecosystems, and aquatic ecosystems was conducted in several watersheds in the Sierra Nevada Mountains to determine if acid deposition was affecting these areas and to infer the implications of acidification on other surface waters in the region.¹⁰⁹⁻¹¹¹ Nitrogen deposition in this region is due to a combination of sources, including power plant emissions, vehicle emissions, and emissions from agricultural activities. Chronic acidification of high elevation surface waters in the Sierra Nevada was not found, but episodic changes in streamwater chemistry did occur. In many of the watersheds studied, for example, pH decreased (waters became more acidic) with increasing runoff, reaching a minimum near peak snowmelt.¹¹¹ In contrast, an accumulating weight of evidence has led some researchers to conclude that high-altitude watersheds in the Colorado Front Range show symptoms of nitrogen saturation (as opposed to acidification).^{43, 44}

Further west, levels of streamwater and groundwater nitrate in the San Gabriel and San Bernardino Mountains have been found to be strongly linked to the magnitude of nitrogen deposition in watersheds throughout the region. Streamwater nitrate concentrations at Devil's Canyon in the San Bernardino Mountains¹¹² and in chaparral watersheds with high smog exposure in the San Gabriel Mountains northeast of



Los Angeles^{113, 114} are the highest in North America for forested watersheds. Chronic nitrogen deposition and nitrate export from these watersheds contribute to the groundwater nitrate problems in the eastern San Gabriel Basin where levels often exceed the federal drinking water standard.¹¹⁴

FOREST ECOSYSTEMS

Current understanding of the effects of acid deposition on forest ecosystems has come to focus increasingly on the biogeochemical processes that affect plant uptake, retention, and cycling of nutrients within forested ecosystems. Research results from the 1990s indicate that documented decreases in base cations (calcium, magnesium, potassium, and others) from soils in the Northeastern and Southeastern United States are at least partially attributable to acid deposition.^{65, 115} Base cation depletion is a cause for concern because of the role these ions play in acid neutralization and, in the case of calcium, magnesium and potassium, their importance as essential nutrients for tree growth. It has been known for some time that depletion of base cations from the soil interferes with the uptake of calcium by roots in forest soils.¹¹⁶ Recent research indicates it also leads to aluminum mobilization¹¹⁷ which can have harmful effects on fish.³⁰

A recent study using strontium isotopes to investigate base cation nutrition in acid deposition impacted forests raises new concerns about the capacity of mineral weathering to replenish exchangeable base cations. Unpolluted temperate forests can become nutritionally decoupled from deeper weathering processes, virtually functioning as atmospherically-fed ecosystems.¹¹⁸ One group of researchers showed that base cation turnover times are considerably more rapid than previously recognized in the plant available pool of soil.¹¹⁸ These results challenge the prevalent paradigm that plants largely feed on rock-derived cations and have important implications for understanding sensitivity of forests to air pollution.

The plant physiological processes affected by reduced calcium availability include cell wall structure and growth, carbohydrate me-

tabolism, stomatal regulation, resistance to plant pathogens, and tolerance of low temperatures.⁵² Soil structure, macro and micro fauna, decomposition rates, and nitrogen metabolism are also important processes that are significantly influenced by calcium levels in soils. The importance of calcium as an indicator of forest ecosystem function is due to its diverse physiological roles, coupled with the fact that calcium mobility in plants is very limited and can be further reduced by tree age, competition, and reduced soil water supply.¹¹⁹

A clear link has now been established in red spruce stands between acid deposition, calcium supply, and sensitivity to abiotic stress. Red spruce uptake and retention of calcium is impacted by acid deposition in two main ways: leaching of important stores of calcium from needles;⁵² and decreased root uptake of calcium due to calcium depletion from the soil and aluminum mobilization.^{115, 120, 121} Acid deposition leaches calcium from mesophyll cells of one-year old red spruce needles,¹²² which in turn reduces freezing tolerance.⁵² These changes increase the sensitivity of red spruce to winter injuries under normal winter conditions in the Northeast, result in the loss of needles, and impair the overall health of forest ecosystems.⁵² Red spruce must also expend more metabolic energy to acquire calcium from soils in areas with low calcium/aluminum ratios, resulting in slower tree growth.¹²⁰

Losses of calcium from forest soils and forested watersheds have now been documented as a sensitive early indicator of the soil response to acid deposition for a wide range of forest soils in the Northeastern U.S.^{53, 69} There is a strong relationship between acid deposition and leaching of base cations from soils in hardwood forests (e.g., maple, oak), as indicated by long-term data on watershed mass balances,^{53, 123} plot- and watershed-scale acidification experiments in the Adirondacks¹²⁴ and in Maine,^{125, 126} and studies of soil solution chemistry along an acid deposition gradient from Minnesota to Ohio.¹²⁷

Although sulfate is the primary cause of base cation leaching, nitrate is a significant contributor in watersheds that are nearly nitrogen saturated.¹²⁸ Recent studies of the decline of sugar maples in the Northeast demonstrate a link between low base cation availability, high levels of aluminum and manganese in the soil, and increased levels of tree mortality due to native defoliating insects.⁷⁴ The chemical composition of leaves and needles may also be altered by acid deposition, resulting in changes in organic matter turnover and nutrient cycling. The sensitivity of hardwood soils to acid deposition is largely controlled by inherent properties and land use; unfortunately, tools to assess present conditions or susceptibility to nutrient



depletion are not readily available or widely applicable. However, recent studies have shown that forest harvesting has the potential to greatly accelerate calcium losses currently experienced due to leaching in low cation soils.¹²⁹

The last NAPAP assessment reported that significant impacts of acid deposition had not been detected over extensive forested areas in the southern pine and pine-hardwood region. That understanding has not changed, and there is very little new information to report for this region. Acid deposition is contributing significantly to the depletion of base cations in many poorly buffered soils where southern pines grow. However, short-term positive effects on tree growth in some nitrogen deficient soils are also expected due to higher levels of nitrogen deposition.²⁹

A significant amount of research has been conducted since 1990 on the effects of nitrogen deposition in the Los Angeles air basin in southern California. Nitrogen enrichment, in combination with ozone exposure, causes major changes in tree health by reducing fine root biomass and carbon allocation below ground and by greatly decreasing the life span of pine foliage.^{130, 131} Nitrogen enrichment results in greater leaf growth, while ozone causes premature leaf loss at the end of the growing season. The net result of these pollutants is significant litter accumulation on the forest floor.¹³² Nitrogen cycling rates in soil are also stimulated by the high nitrogen inputs, resulting in large leachate losses of nitrate from these watersheds and elevated fluxes of nitric oxide gas from soil.^{51, 112, 132} In coastal sage ecosystems that occur in the low elevation sites, greenhouse and field studies indicate that nitrogen deposition may be one factor enhancing the invasion of exotic annual grasses.^{133–135} Recent controlled exposure studies demonstrate that nitric acid vapor (HNO_3), a component of photochemical smog, injures leaves of wildland shrub and tree species at near-ambient doses in the Los Angeles air basin.¹³⁶

COASTAL ECOSYSTEMS

Nitrogen is present in high enough quantities in many coastal ecosystems to be identified as a pollutant. There are many sources of nitrogen to estuaries and coastal waters, including point discharges from wastewater treatment plants, urban and agricultural runoff, and atmospheric deposition. Since 1990, a large amount of research has been conducted on the impact of nitrogen deposition to coastal waters. It is now known that nitrogen deposition is a significant source of nitrogen to many estuaries.^{137, 138} The amount of nitrogen entering estuaries due to atmospheric deposition varies widely, depending on the size and location of the estuarine watershed and other sources of nitrogen in the watershed. There are a handful of estuaries where

atmospheric deposition of nitrogen contributes well over 40% of the total nitrogen load; however, in most estuaries where estimates exist, the contribution from atmospheric deposition ranges from 15–30% (see Table 1). The areas with the highest deposition rates stretch from Massachusetts to the Chesapeake Bay, and along the central gulf coast.

Nitrogen is often the limiting nutrient in coastal ecosystems. Increasing the levels of nitrogen in coastal waters can cause significant changes to those ecosystems. Approximately 60% of estuaries in the U.S. (65% of the estuarine surface area) suffer from over-enrichment of nitrogen, a condition known as eutrophication.⁸³ Symptoms of eutrophication include changes in the dominant species of plankton (the primary food source for many kinds of marine life) that can cause algal blooms, low levels of oxygen in the water column, fish and shellfish kills, and cascading population changes up the food chain. In addition, increased levels of turbidity in the water due to large amounts of algae can kill off submerged aquatic vegetation (SAV), which is important habitat for many estuarine fish and shellfish species. Many of the most highly eutrophic estuaries are along the gulf and mid-Atlantic coasts, overlapping many of the areas with the highest nitrogen deposition, but there are eutrophic estuaries in every region of the conterminous U.S. coastline.

Materials and Structures

SO_2 and NO_x emissions, as well as many of the compounds they form in the atmosphere, are damaging certain materials, primarily cultural resources made of stone. Bronze, paint, and other surfaces and surface coatings are also susceptible to damage from acid pollutants and deposition. Weathering due to acid deposition often harms cultural assets (e.g., statues and monuments) more than purely operational resources (e.g., bridges and buildings). This is because the appearance of cultural resources, where much of their value lies,



TABLE 1. Nitrogen contribution to estuaries in the United States from atmospheric deposition (direct and indirect)

ESTUARY	RANGE OF NITROGEN LOAD DUE TO ATMOSPHERIC DEPOSITION	ESTUARY	RANGE OF NITROGEN LOAD DUE TO ATMOSPHERIC DEPOSITION
Casco Bay	30–33%	St. Catherine's and Sapelo Sounds	33–45%
Great Bay	11–17%	Altamaha River	8–23%
Merrimack River	14–28%	Indian River	14–75%
Massachusetts Bay	12–14%	Charlotte Harbor	8–19%
Buzzards Bay	23–51%	Sarasota Bay	26%
Narragansett Bay	16%	Tampa Bay	11–22%
Gardiners Bay	86%	Apalachee Bay	17–27%
Long Island Sound	19–39%	Apalachicola Bay	8–16%
Hudson River/ Raritan Bay	10–27%	Mobile Bay	11–25%
Barnegat Bay	27–58%	West Mississippi Sound	24–35%
New Jersey Inland Bays	26–35%	Barataria Bay	25–28%
Delaware Bay	16–25%	Terrebonne/Timbalier Bays	60–65%
Delaware Inland Bays	38%	Calescieu Lake	16–20%
Maryland Inland Bays	24%	Sabine Lake	11–21%
Chesapeake Bay	23–33%	Galveston Bay	16–18%
Pamlico Sound	17–28%	Matagorda Bay	16–33%
Winyah Bay	7–19%	Corpus Christi Bay	16–30%
Charleston Harbor	7–23%	Upper Laguna Madre	16–23%
St. Helena Sound	10–22%	Lower Laguna Madre	12–18%

Source: Valigura, R.S., R.B. Alexander, M.S. Castro, T.P. Meyers, H.W. Paerl, P.E. Stacey, and R.E. Turner, 2001. Nitrogen Loading in Coastal Water Bodies: An Atmospheric Perspective. American Geophysical Union (See #137 in References section.)



is particularly vulnerable to damage. There are also historic and emotional values attached to cultural assets that increase the value of their preservation.

A recent review of the scientific literature on the contribution of acid deposition to stone deterioration indicates that dry deposition, which is mainly influenced by short-range transport of pollutants from local sources, is the main source of damage.⁸⁸ A secondary source of damage is wet deposition from long-range transport of pollutants. In areas where buildings and monuments remain wet for long periods of time, and in rural areas, wet deposition can

be a major source of damage. If pollution is very low, this phenomenon becomes indistinguishable from the “normal” weathering of stone due to the dissolution effect from pure water.⁸⁸

Although the details of the mechanisms involved in pollutant-induced deterioration of materials are not fully understood, various kinds of research are expanding the base of knowledge available to address the problem. Damage to stone from acid deposition is a complex process that depends upon many factors. The type of stone, how it weathers, the porosity and texture of the stone, and even how it is cleaned, all contribute to the type and rate of damage. Geographic location and the natural environment of the stone also affect the extent and magnitude of damage. For example, stone degradation rates are negligible in dry

areas such as the Southwestern United States.

Stone weathering involves interactions between ever changing meteorological variables—rain, wind, temperature, humidity, and continually changing complex stone surfaces. The way water flows over a carved stone surface influences the mobilization of salts and particulate materials on the surface and can change the stone's chemistry and porosity. A slight change in the overall shape of the surface, either due to weathering or by design, may change the way water flows over the surface and can radically influence the erosion and soiling patterns.²⁹

The porosity of the stone is another critical factor within the deposition process. Once sulfur dioxide gets into the pores, it is difficult to get out. Cleaning treatments have the potential to change the surface texture; therefore, some cleaning methods may result in increased pollutant deposition and subsequent damage to the building stone.

Although scientists continue to study stone systems and describe the uptake of air pollution by stone, it is unlikely that research will define dose-response functions in the near future. Research to date leads scientists to believe that there is no pollution threshold below which no damage will occur; rather, any amount of SO₂ will lead to some level of deterioration. In addition, the time it takes for stone to respond to pollution is extremely long; effects can appear 25, 50, or even 100 years after exposure.²⁹ This understanding has led recent research efforts to focus more on treatments and mitigation for existing damage and methods to prevent damage to stone structures. However, preliminary attempts at preventing damage and restoring materials have met with limited success.

Research is progressing on the development of new treatments to strengthen stone, including limestone and marble, that has been degraded by SO₂.^{139, 140} Chemical interactions between SO₂ and stone leads to the formation of calcium sulfate, or gypsum. Because calcium sulfate is relatively water soluble, rain can dissolve and remove material, including the cementitious materials that bind the grains of stone together. The result is a weak, "sugaring" stone. Several methods are being investigated to strengthen these types of stone. One is ethyl silicate-based consolidants. The main limitation of using these products is their reported cracking behavior during drying. A more promising method under investigation is particle modified consolidants. These compounds consist of a silicate matrix plus colloidal oxide particles that are used to consolidate degraded stone. The presence of the particles physically limits the silicate network from shrinking under capillary pressure, and thereby reduces strength loss during drying.

In addition, because the dried consolidants remain porous, the network maintains a higher permeability.

In addition to this work on stone, additional research is focused on developing new coating systems to protect outdoor bronze.¹⁴¹ Atmospheric pollutants such as SO₂, NO_x, CO₂, and chlorides affect various materials including bronze, and cause greater corrosion. The research explores new coating technologies that would be appropriate for outdoor bronze sculptures. The coatings currently under investigation include a fluorocopolymer blended with various acrylics, conductive polymers, BTA pretreatments, and a very fine titanium dioxide. These coatings are being studied on both rolled bronze and satin-finish, cast monumental bronze substrates using electrochemical impedance spectroscopy.

Human Health

Scientific understanding of the human health effects of fine particles has changed dramatically since 1990. In 1996, EPA published *Air Quality Criteria for Particulate Matter* ("Criteria Document"), a comprehensive review and summary of the scientific literature.¹⁴² At that time, a large body of epidemiological evidence indicated that serious health effects were associated with PM at levels even below the then-current air quality standards. These health effects include:

- Premature death and increased hospital admissions and emergency room visits, especially for heart and lung diseases, primarily in the elderly and individuals with pre-existing cardiopulmonary disease.
- Increased respiratory symptoms and disease, primarily in children and individuals with cardiopulmonary disease such as asthma.
- Decreased lung function, particularly in children and individuals with asthma.
- Alterations in lung tissue and structure and in respiratory tract defense mechanisms.



The epidemiology studies provided evidence for effects with both acute (e.g., hours or days) and long-term (e.g., months or years) exposures to PM. Important uncertainties remained, however, such as issues related to the interpretation of the role of gaseous co-pollutants in PM associations with health effects and the lack of accepted biological mechanisms that could explain observed effects.

An unprecedented number of new studies containing further evidence of serious health effects have been published since the 1996 Criteria Document, with important new information coming from epidemiological, toxicological, controlled human exposure, and dosimetry studies. For example, important new epidemiological studies include multi-city studies that use uniform methodologies to investigate the effects of PM on health with data from multiple locations with varying climate and air pollution mixes.¹⁴³ The multi-city studies have increased confidence that the associations found with PM are not an artifact of associations with potential confounders such as the gaseous co-pollutants. In addition, a comprehensive validation and reanalysis study has used data from two cohort studies (the “six cities” and American Cancer Society cohorts); the results have generally supported the findings of the earlier studies showing associations between premature mortality and long-term PM exposure.¹⁴⁴

Many epidemiology studies have used measurements of PM₁₀ or other PM indicators. As stated previously, the full body of scientific studies provided consistent and coherent evidence that adverse health effects were associated with ambient PM. A number of the new studies used measured fine particle concentrations (e.g., PM_{2.5}) or other fine particle indicators (e.g., sulfates, black smoke). This group of studies indicated that fine particles are likely important contributors to the observed PM-associated effects. A number of new studies have evaluated independent associations between effects and fine- and coarse-fraction particles, and the results support the earlier studies’

findings of associations between serious health effects and ambient fine particles. Other organizations have reviewed the health evidence and drawn similar conclusions; for example, Health Canada and the World Health Organization have recently published scientific reviews, finding that it is largely the fine fraction of particulate matter that is involved in exacerbations of cardiorespiratory disease.^{145, 146}

In addition, new toxicological and controlled human exposure studies have provided insight into potential mechanisms for PM-related effects. These studies include animal and controlled human exposure studies using concentrated ambient particles, new indicators of response (e.g., heart rate variability), as well as animal models representing sensitive subpopulations. Some potential mechanisms and the available evidence regarding those mechanisms have been summarized in recent review articles.^{147, 148} These potential mechanisms include effects of oxidative stress in the respiratory tract, effects on the autonomic nervous system, changes in the blood system to increase coagulability of the blood, or lung injury and inflammation. While evidence is not available to fully support any of these mechanisms, it is likely that there will be multiple mechanisms underlying the range of PM-related health effects.

For additional information on the latest research regarding the health impacts of fine particles, see “Air Quality Criteria for Particulate Matter” (October 2004) volumes I & II, which can be found at <http://cfpub2.epa.gov/ncea/cfm/recordisplay.cfm?deid=87903>

Modeling

Researchers have used models to help them understand and predict atmospheric, environmental, and human health responses to acid deposition for well over 20 years. Since 1990, there have been significant improvements in atmospheric modeling capabilities due to better understanding of the atmospheric chemistry and physics that play a role in transport and deposition of acid compounds, as well as significant improvements in computing capabilities. New models have also been developed that allow researchers to model sulfur and nitrogen transport and deposition nationwide (previously used models for NA-PAP covered only the Eastern U.S.). Watershed modeling capabilities have also improved as researchers are continuing to refine and expand models that project acidification of waterbodies. A significant amount of research published since 1990 detailing how fine particle concentrations adversely impact human health has made human health benefits modeling an integral part of the assessment of the benefits of Title IV.



ATMOSPHERIC MODELING

Model developments have continued, especially for intended application in other parts of the world. In Europe, the Multi-layer Acid Deposition model for Europe (MADE-50) has been developed to address the deposition of a range of sulfur and nitrogen species.¹⁴⁹ For application in Asia, the Sulphur Transport Eulerian Model 2 (STEM-II) has been expanded to address a number of chemical species, including photochemical oxidants. Many other models have been developed, some addressing seasonal and annual averages and others targeting shorter periods of intensive investigation.¹⁵⁰

Nonlinear Responses to Decreases in SO₂ and NO_x Emissions

The relationships between reductions in SO₂ and NO_x emissions and changes in sulfate and nitrate formation involve a complex group of gas- and aqueous-phase chemical reactions between acid deposition and aerosol precursors and oxidants. These reactions can produce nonlinear responses to emission reductions.¹⁵¹ For example, reducing NO_x while leaving SO₂ unchanged can lead to an increase in sulfate formation under certain conditions. Reducing NO_x emissions could increase the concentrations of the oxidant hydrogen peroxide (H₂O₂).

Similarly, reducing SO₂ but not NO_x could, under certain conditions, lead to increased nitrate formation. In gas-

phase/aqueous-phase chemistry, ammonia preferentially neutralizes sulfate over nitrate to form ammonium sulfate aerosols. If SO₂ is reduced, the excess ammonia that becomes available can neutralize nitric acid and form ammonium nitrate aerosols. These aerosols absorb gas-phase nitric acid, which increases the formation of particle nitrate.

This non-linear chemistry makes it important to reduce emissions of SO₂ and NO_x simultaneously whenever possible to get the full health and environmental benefits of reduced particle formation.

WATER/WATERSHED MODELING

The Model of Acidification of Groundwater in Catchments (MAGIC) is a prominent model developed to estimate acidification of lakes and streams in response to sulfur deposition.^{152–154} MAGIC was the principal model used by NAPAP to estimate future damage to lakes and streams in the Eastern United States in the *1990 Integrated Assessment*. MAGIC is a lumped-parameter model of intermediate complexity, developed to predict the long-term effects of acidic deposition on



SPOTLIGHT: ADVANCES IN ATMOSPHERIC MODELING

Throughout the 1980s, the scientific community dedicated significant resources to developing acid deposition modeling capabilities. The NAPAP *1990 Integrated Assessment* primarily relied on a then state-of-the-art model called the Regional Acid Deposition Model (RADM). RADM was developed beginning in 1985 under the auspices of NAPAP to address policy and technical issues associated with acid deposition.³¹ The model was designed to provide a scientific basis for predicting changes in deposition resulting from changes in sulfur and nitrogen emissions, to predict the influence of emission sources in one region on acid deposition in other regions, and to predict the levels of acid deposition in certain sensitive receptor regions.

The basic framework for acid deposition models has not changed since 1990. No major overhauls have been made; rather, the understanding of particular chemical and physical interactions has improved, and it has been possible to incorporate more complex aspects of atmospheric modeling physics and chemistry into acid deposition models. In addition, improvements in inventories make the data fed into the models more accurate, which improves overall model accuracy and credibility. Finally, improvements in computing power allow computers to do more calculations in less time, improving the speed at which models can operate, broadening the types of computers on which models can be run, and expanding the practical limit of complexity a model can achieve.

There are a large number of atmospheric and deposition models that have been used to assess the relationship between emissions and

acid deposition. The following are general descriptions of the most commonly used models in the U.S.

- **Regional Acid Deposition Model (RADM).**

RADM has been improved over the past decade by upgrading various modules to better represent the governing physical and chemical atmospheric processes. The most recent version is RADM 2.61. The Regional Particulate Model (RPM) is an extension of RADM that includes the chemistry and dynamics of atmospheric aerosol particles.¹⁵⁵ The full-scale version of RADM is resource-intensive and has typically been applied on supercomputers. While the model is primarily designed for episodic applications, it has also been used to understand long-term relationships between changing emissions patterns and pollutant concentrations and deposition using an episode aggregation technique. RADM and RPM have been applied primarily to eastern North America; An international version of RADM, EURAD, has been applied in Europe.^{155, 156} RADM has also been used to identify emission source-regions affecting the Chesapeake Bay watershed.¹⁵⁷

- **Regulatory Emissions Modeling System for Aerosols and Deposition (REMSAD).** REMSAD was developed by ICF Consulting for the EPA. It is based on an Eulerian (grid) approach and may be applied at scales ranging from a single metropolitan region to a continent containing multiple urban areas. It was designed to be capable of simulating the complex long-range transport and deposition of atmospheric pollutants to aquatic environments and to assess the relative impacts of alternative control strategies. Although initially developed to study the transport and removal of airborne toxics, the interdependence of the processes that also control the formation and removal of particles was recognized, and therefore the model was designed for both toxics and particulate matter applications. Annual simulations of the entire U.S. are practical.

- **Community Multi-scale Air Quality (CMAQ).**

Models 3-CMAQ was developed by EPA to evaluate the impact of multiple pollutants at multiple temporal and spatial scales. The Models-3 framework provides tools to prepare emissions and meteorological inputs, define emissions control strategies, project future emissions inventories, execute meteorological models, delineate a geographic domain, select alternative atmospheric chemical reaction mechanisms, set vertical and horizontal grid resolutions, and manage a series of air quality model runs. CMAQ is applied through the Models-3 system. It contains state-of-the-science simulations of atmospheric transport processes, atmospheric chemistry, aerosol dynamics and chemistry, cloud chemistry and dynamics, and deposition processes. A key aspect of the Model-3/CMAQ system's structure is its flexibility to incorporate scientific and modeling advances, to test alternative modeling approaches, and to link with human and ecosystem exposure models. In addition to combining point and area source emissions into a single three-dimensional hourly file as in RADM, CMAQ provides the option of treating large point sources separately using a plume-in-grid approach that has a gridded structure that expands as the plume moves downwind.

- **Acid Deposition and Oxidant Model (ADOM).** The ADOM is a comprehensive three-dimensional Eulerian episodic model developed in the 1980s in parallel with RADM. RADM and ADOM are the two comprehensive models that were used for the NAPAP 1990 *Integrated Assessment*. The development of ADOM was sponsored by the Ontario Ministry of the Environment, the Atmospheric Environment Service of Environment Canada, the German Umweltbundesamt, and the Electric Power Research Institute. ADOM is primarily intended for episodic applications because of its computational resource requirements. An episode aggregation technique, however, based on the approach developed for RADM during NAPAP, has been developed for predicting changes in annual deposition resulting from changes in



emissions.¹⁵⁸ Like RADM, ADOM has been primarily applied to eastern North America. The reduced form, regional haze version of the model (VISHWA) has been applied to the western part of North America (including southern Canada and northern Mexico), while the mercury version of the model (TEAM) has been applied to the entire contiguous United States. ADOM has not been significantly updated since 1992. Many improvements are currently being made by Environment Canada, which is building the successor to ADOM, referred to as the AES Unified Regional Air Quality Modeling System (AURAMS), using existing and new modules as appropriate.

- **Advanced Statistical Trajectory Regional Air Pollution (ASTRAP).** The ASTRAP model, developed at Argonne National Laboratory in the early 1980s, is a Lagrangian model designed to simulate long-term (annual or seasonal) average concentrations and deposition fluxes. ASTRAP was used as the atmospheric pathways module of the Tracking and Analysis Framework (TAF) for the 1998 NAPAP report.²⁹ The treatments of chemistry and dry and wet removal in ASTRAP are relatively simple compared to the Eulerian models described in this section. Because of the model's simplicity, ASTRAP can be applied for long-term simulations and with relatively little computer cost. While

much of the basic chemistry is well-represented in the model, it fails to treat aerosols or the non-linearity of the aqueous-phase SO_2 /sulfate chemistry. Therefore, a key use of the model is as a screening tool to identify scenarios to be run in more complex models.

- **Urban and Regional Multiscale Model (URM).** The URM model is a three-dimensional Eulerian grid model designed primarily for episodic simulations. The model evolved from the CIT (Carnegie Mellon/California Institute of Technology) airshed model developed and upgraded over a 20-year period¹⁵⁹⁻¹⁶¹ and is now available in the public domain from the Georgia Institute of Technology. URM can be run on a workstation but the model is moderately difficult to use, and users must receive initial guidance and training. URM was recently extensively updated as part of the southern Appalachian Mountains Initiative (SAMI) program to incorporate cloud and aerosol processes. SAMI is also evaluating the new version of the model by comparing model predictions of ozone, particulate sulfate, nitrate, ammonium, soil, organic aerosols, elemental carbon, $\text{PM}_{2.5}$ and PM_{10} concentrations and sulfate, nitrate, ammonium, and hydrogen ion wet deposition with corresponding measurements from 22 sites.



surface water chemistry. The model simulates soil solution chemistry and surface water chemistry to predict the monthly and annual average concentrations of the major ions in waterbodies. At the heart of MAGIC is the size of the pool of exchangeable base cations in the soil. As the fluxes to and from the pool change over time due to changes in atmospheric deposition, the chemical equilibria between soil and soil solution shift to give changes in surface water chemistry.

The original data collected on acidification in lakes and streams, the National Surface Water Survey (NSWS), used statistically representative methods to sample approximately 28,000 lakes and 56,000 stream reaches in the U.S.³⁶ The MAGIC model predicts changes in lakes and streams that are a statistically representative subset of the waterbodies

from the NSWS survey and, therefore, of the region being modeled. Therefore, within the limitations of the NSWS survey (primarily the limitation that it only sampled lakes larger than 4 hectares), the MAGIC model can estimate the level of acidification in waterbodies throughout the entire Adirondack, northeastern, and southeastern Appalachian regions of the U.S. Although there are some uncertainties with regard to the model, particularly concerning watershed nitrogen dynamics, MAGIC provides a generally accurate, well-tested, and widely accepted tool for modeling the response of surface water chemistry to sulfur deposition.

PnET-BGC is an integrated biogeochemical model that simulates the concentrations and transport of major elements, including nitrogen, in forest vegetation, soil, and water. The model enables simultaneous simulation of major element cycles in forest and interconnected aquatic ecosystems.¹⁶² PnET-BGC uses measured and estimated data on meteorology and atmospheric deposition to simulate estimates of changes in atmospheric deposition from 1850 to the present day. Future scenarios of changes in atmospheric deposition are simulated using projections provided from air quality modeling based on model runs of air emission control scenarios. PnET-BGC has primarily been applied to forest watersheds in the Northeastern U.S.

HEALTH EFFECTS MODELING

When the Clean Air Act Amendments were passed in 1990, the health effects of fine particles were just beginning to be understood. In the years since, a series of studies have demonstrated the relationship between exposure to fine particles and a series of health impacts, including premature mortality and asthma attacks.¹⁶³ As a result of this new understanding, NAPAP now includes the estimated health benefits of SO₂ and NO_x emission reductions and the monetary impact of those benefits as part of its analysis of the impacts of Title IV.

EPA developed a new methodology for quantifying and monetizing the health benefits of improved air quality as part of EPA's Report to Congress in 1999 entitled *The Benefits and Costs of the Clean Air Act 1990–2010*.¹⁶⁴ Each phase of the Report's preparation, which spanned nearly three years, was thoroughly reviewed by academic and industry experts serving on EPA's Science Advisory Board Council on Clean Air Compliance Analysis. Currently, health benefits are calculated using the same concentration-response functions and economic valuation functions that EPA uses in analysis of major rules that address fine particles and ozone.

The air quality modeling data serve as inputs to both the Benefits Model for Air Quality (BenMod) and the Benefits Mapping and Analysis Program (BenMAP), two different modeling systems that translate air quality changes to changes in health outcomes (e.g., premature mortality, emergency room visits, cases of chronic bronchitis, asthma attacks) through the use of concentration-response functions. Peer-reviewed, published scientific literature on the health effects of air pollutants provides the source of these concentration-response functions. Health benefits are related to the change in air pollutant exposure experienced by individuals. Because the expected changes in pollutant concentrations vary from location to location, individuals in different parts of the country may not experience the same level of health benefits. Benefits are apportioned among individuals by matching the change in air pollutant concentration change with the size of the population that experiences that change. Using the expected population exposure, the concentration-response functions are applied to derive estimates of the number of incidences of the health outcomes that are associated with change in exposure to ambient particulate matter and ozone.



Chapter 4: Expectations for Full Implementation of Title IV in 2010

By 2010, emissions of SO₂ are projected to be approximately 9.86 million tons, less than a million tons above the cap of 8.95 million tons, and approximately three million allowances are projected to be in the allowance bank. Emissions are expected to reach the level of the cap after 2010 once the power sector has depleted the allowance bank. Air quality in 2000–2002 reflects the significant emission reductions that have already occurred since Title IV was passed. Air quality is expected to continue to improve as emissions approach the level of the cap. Some lakes and streams, particularly in the Northeast, are expected to begin showing signs of recovery from acidification; however, recovery is expected to continue for decades after 2010 due to the fact that soils and biological communities recover more slowly than air quality or deposition improvements occur. A recent estimate of the human health benefits of Title IV indicates that the benefits are substantial.



This analysis of full implementation of Title IV in 2010 includes emissions modeling, air quality modeling, and freshwater quality modeling. It also includes an estimate of the health benefits of Title IV reported in the literature. Estimates of emissions, air quality, and acid deposition were projected for 2010 and compared to averaged monitored data from 1989–1991, before Title IV was passed. Although the SO₂ allowance bank will still be in use in 2010, analysts have used that date, twenty years after Title IV was passed and ten years after Phase II began, as the marker for the time when emissions are close to the level of the 2010 cap and most of the emission reductions are expected to have taken place. The freshwater quality modeling projects conditions in 2030 and compares them to conditions in 1984 or 1985. The health benefits estimate relies on estimates of air quality changes and the annual benefits per ton of reducing emissions of SO₂.

Emissions modeling from power plants was conducted using the 2003 version of the Integrated Planning Model (IPM). IPM is an economic model that predicts emissions from the power sector due to changes in environmental regulations and the costs of various emission control options.

To provide a more comprehensive understanding of the state of the environment in 2010, the 2010 projections of emissions from power plants are based on implementation of

Title IV and the NO_x SIP call and several state regulations that were finalized before April 2003. (See text box “What Will Air Quality be Like in 2010?” on page 58.) They do not include any co-benefits that might be achieved from implementation of mercury controls on power plants, any possible New Source Review determinations or other administrative or legal agreements, reductions undertaken in order to meet the National Ambient Air Quality Standards (NAAQS) for which states are required to submit implementation plans by 2007, the Clean Air Interstate Rule (CAIR), the BART Rule, any additional actions taken by Congress, or any further reductions from sources in Canada. Mobile source rules will also result in NO_x reductions as they are implemented. The 2010 emissions projections were compared to 1990 emissions data collected by the EPA.

The air quality and deposition modeling analyses were conducted using REMSAD (see page 54 for a description of REMSAD). The scenario used was a 2010 Title IV implementation scenario that includes the SO₂ and NO_x emissions in 2010 with Title IV as projected by IPM (the “with Title IV” run). The scenario also includes NO_x emission reductions from power plants and industrial boilers due to the NO_x SIP call and finalized state emission reduction programs. Stationary and area sources were modeled in the scenario as projected emissions in 2010 as estimated based on the 1996 National Emissions Inventory (NEI). The scenario does not reflect future reductions from mobile source programs. The results of the 2010 Title IV implementation scenario were scaled to monitoring data by comparing a 2001 baseline modeled scenario to 1999–2001 monitoring data. This allows a comparison of 2010 modeled projections of full implementation of Title IV with monitoring data from before the program took effect (1989–1991).

The magnitude of emission reductions affects both the amount of recovery that takes place in a lake or stream and the rate at which that recovery occurs.³⁰ Lake conditions in the Adirondacks and Northeast and stream conditions in the Southeast were modeled using the MAGIC model (see page 53 for a description of MAGIC). These regions were chosen because they are among the most acid-sensitive ecosystems and are downwind of many of the emission sources affected by the Acid Rain Program. SO₂ emissions under Title IV were assumed to continue to decrease during the model run time frame; emissions from

electric generating sources in 2030 were estimated to be approximately 9 million tons). Projected lake and stream conditions were compared to modeled estimates of lake and stream conditions in 1984 and 1985. Since lake and stream quality in 2010 would represent only a very small portion of the recovery expected due to Title IV, lake and stream conditions for 2030 are considered a more appropriate representation of the environmental benefits of Title IV.

Emissions

As a result of Title IV, emissions of SO₂ are expected to be 9.86 million tons in 2010, less than a million tons above the annual allocation (cap) of 8.95 million tons. Emissions can be above the cap because it is expected that on January 1, 2010, the bank of unused allowances will still contain approximately 3 million allowances available for use. The SO₂ bank was created when affected sources overcomplied with the emission reduction requirements during the first years of the program. During Phase I, emissions were 25–40% below allowable levels, resulting in larger human health and environmental benefits during those years. NO_x emissions from power plants are expected to be 3.94 million tons in 2010, approximately 500,000 tons below where they are now. This 40% reduction from the 1990 level of 6.7 million tons is due to reductions under both Title IV and the NO_x SIP call. Note that implementation of CAIR is expected to reduce emissions of SO₂ and NO_x to 6.1 million tons and 2.4 million tons, respectively, in 2010.

Acid Deposition

Air concentrations respond very quickly, in a matter of hours to days, to changes in SO₂ and NO_x emissions. Therefore, while NAPAP expects some small additional emission reductions to take place after 2010, air quality in 2010 reflects the vast majority of the improvement in air quality that is expected to occur due to Title IV. The data presented in Chapter 2 on the status and trends of air concentrations of SO₂ indicate that Title IV has substantially reduced concentrations of SO₂ and sulfate. This reduction in air concentrations has occurred in many heavily populated areas where concentrations of SO₂ and sulfate in the air cause respiratory, cardiac, and other health problems. This improvement in air quality, therefore, is expected to result in improvements in human health, as discussed below.

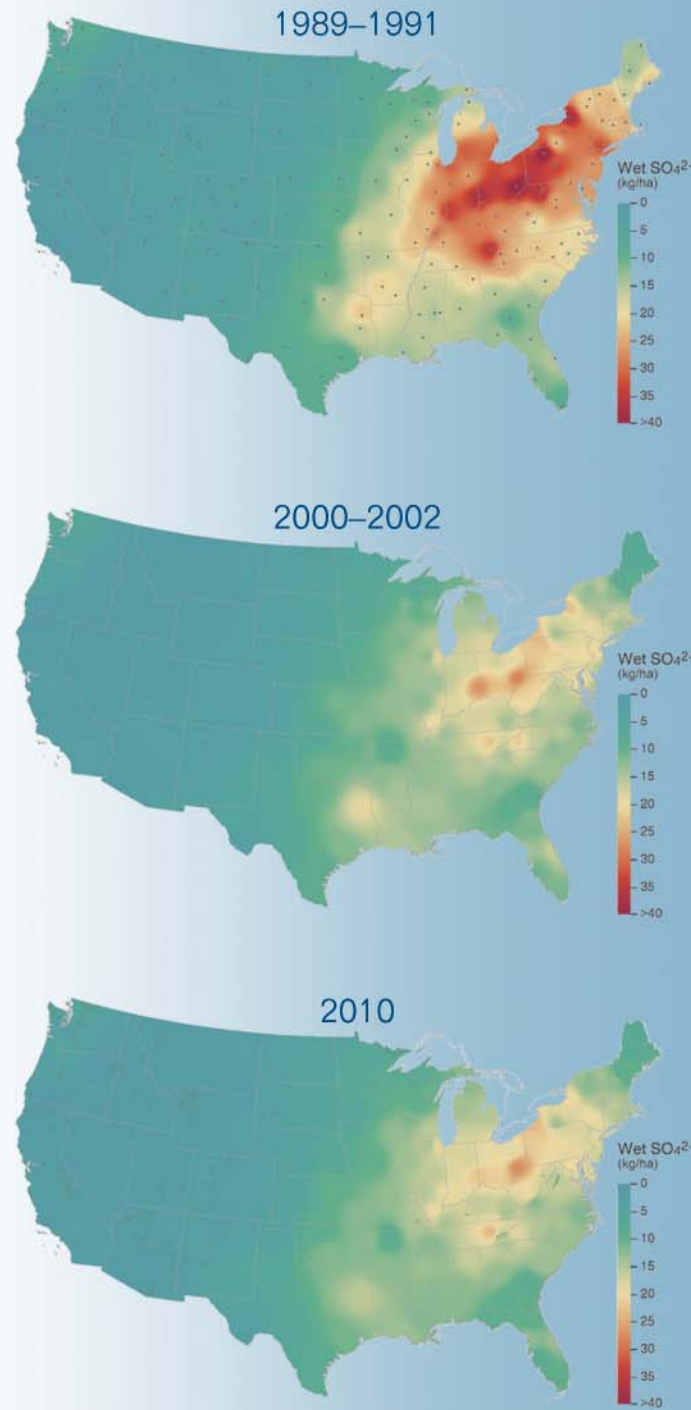
Acid deposition also responds quickly to reductions in emissions of SO₂ and NO_x. Therefore, as is the case with air quality, NAPAP believes that the acid deposition rates in 2010 reflect the vast majority of the reductions in deposition expected due to Title IV. Most of these reductions in acid

WHAT WILL AIR QUALITY BE LIKE IN 2010?

Predictions are always risky, but NAPAP believes it is important to estimate the environmental effects of Title IV once the program has been fully implemented. For this analysis, NAPAP chose to predict the status of several environmental indicators based on emissions changes expected from programs that affect the power industry that were already “on the books” when the modeling was conducted (2002–2003). While this projection provides an appropriate perspective from which to evaluate Title IV, the state of the environment in 2010 is likely to be different from what is predicted here due to additional SO₂ and NO_x emission reductions resulting from implementation of CAIR, future emission standards for mobile sources, and state actions to meet the fine particle and ozone National Ambient Air Quality Standards. In 2010, CAIR is expected to reduce SO₂ emissions to 6.1 million tons annually nationwide (5.1 million tons in the Eastern U.S.), an approximately 40% reduction from 2003 emissions levels (approximately 45% reduction in the Eastern U.S.). Similarly, nationwide NO_x emissions from power plants are expected to be 2.4 million tons annually in 2009, an approximately 40% reduction from 2003 levels. These emissions are approximately 60% lower than 1990 emissions of both SO₂ and NO_x. Beyond 2010, SO₂ and NO_x emissions are expected to continue to decline, reaching reductions of 70% from 2003 levels, as CAIR and other rules mentioned above are fully implemented.



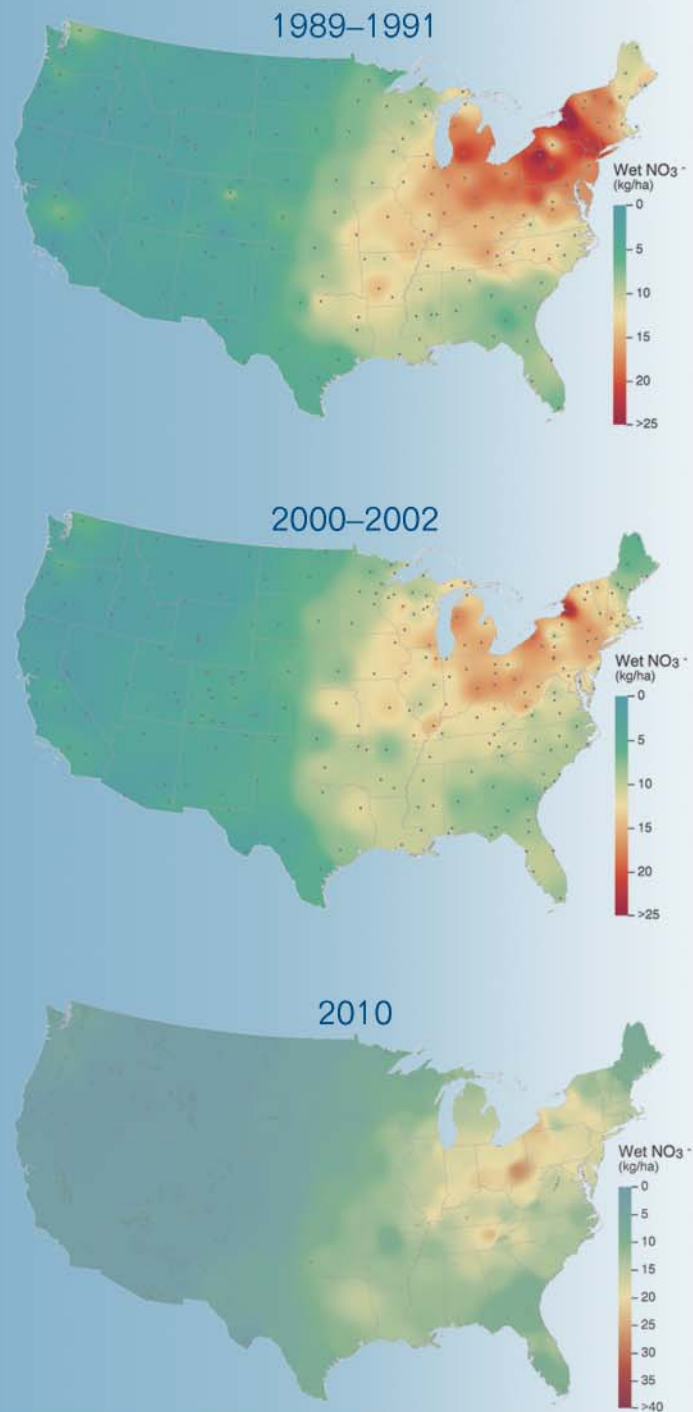
FIGURE 30. Projected change in wet sulfate deposition in 2010 with Title IV compared to conditions in 1989–1991 and 2000–2002



Source: NADP and EPA.

As indicated on page 57, these projections do not include emission reductions as a result of CAIR, any mobile source regulations, or any state regulations finalized after April 2003.

FIGURE 31. Projected change in inorganic wet nitrogen deposition in 2010 with Title IV compared to conditions in 1989–1991 and 2000–2002



Source: NADP and EPA

As indicated on page 57, these projections do not include emission reductions as a result of CAIR, any mobile source regulations, or any state regulations finalized after April 2003.

deposition have already taken effect, but some additional reductions in both sulfur and nitrogen deposition are expected by 2010.

The largest reductions in sulfur deposition are expected in the Ohio River Valley and in downwind areas, including the acid-sensitive regions of the Northeast and mid-Atlantic (see Figure 30). Some additional reductions in deposition in the Midwest and Northeast beyond what has occurred by 2000–2002 are expected as emissions continue to drop to the level of the cap.

Wet sulfate deposition is expected to be significantly lower in 2010 than it was in 1989–1991. This reduction in sulfate deposition has already led to improvements in the health of some acid-sensitive lakes and streams, particularly those in the Adirondacks, northern Appalachian Mountains, and the upper Midwest, as discussed in Chapter 2.

Wet inorganic nitrogen deposition (deposition of nitrate and

ammonium) is also expected to continue to decline substantially between 2000–2002 and 2010. This is in addition to the large reductions that occurred between 1989–1991 and 2000–2002 (see Figure 31). This is primarily due to implementation of the NO_x SIP call, which reduces emissions of NO_x from power plants, industrial boilers, and other sources in the Eastern U.S.

Acidification of Freshwater Lakes and Streams

Throughout acid-sensitive ecosystems in the Eastern U.S., acid deposition alters soils, stresses forest vegetation, acidifies lakes and streams, and harms fish and other aquatic life. For example, some acidified lakes in the

WHY ARE THE ACIDIFICATION NUMBERS DIFFERENT?

The extent of acidification as measured by the TIME/LTM monitoring sites in the Adirondacks is different than that reported in the modeling assessment reported in this analysis. This difference is due to differing types of Adirondack lakes included in each assessment.

Since the original acid rain surveys were conducted in the 1980s, researchers have continued to refine their understanding of how to best measure changes in acidification due to anthropogenic causes. Researchers currently model a different subset of lakes and streams than were modeled in the 1980s and early 1990s. This change in “model population” means that current modeled predictions are somewhat different from the monitoring data reported in the 1990 NAPAP Integrated Assessment or the 2003 EPA Response of Surface Water Chemistry to the CAAA report. The original NAPAP assessment, and the subsequent EPA report, are based on data collected during the National Surface Water Survey (NSWS). These waterbodies, known as NSWS lakes and streams, were selected to be statistically representative of the region being sampled. The purpose of the NSWS was to assess lakes and streams that were acidic due to anthropogenic activities. In the Adirondacks, lakes smaller than 4 hectares (10 acres) and greater than 2,000

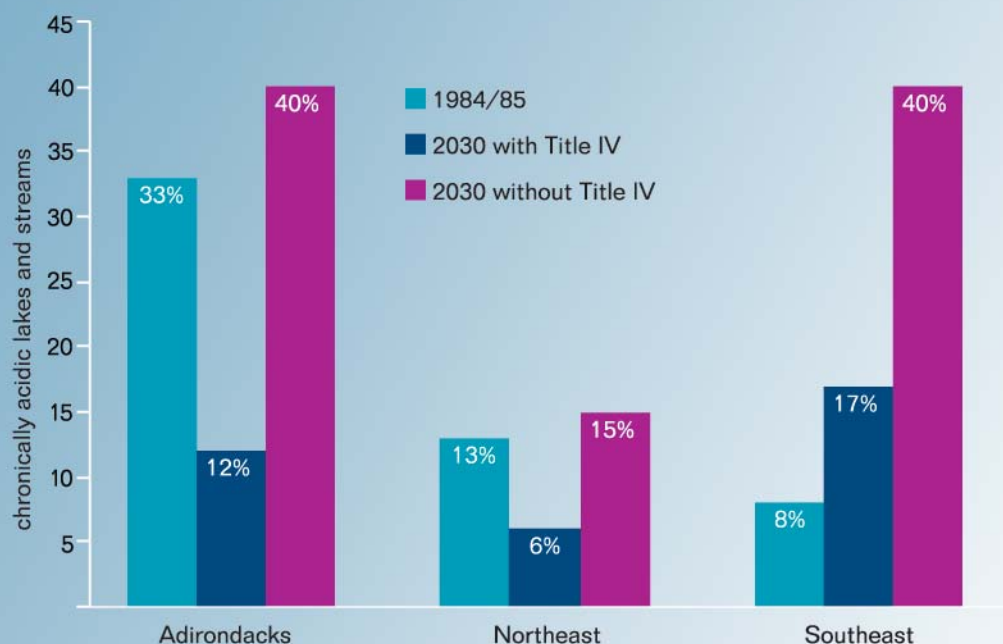
hectares (5,000 acres) were not sampled because it was thought they were more strongly affected by organic acidity.

The NSWS lakes and streams were further classified and subdivided based on several characteristics. A project to assess the rate of response of waterbodies to acidification (the Direct/Delayed Response Project, or DDRP), used a subset of NSWS lakes that had lower ANC values (<400 ueq/L), had depths greater than 1.5 m deep, were smaller than 3,000 ha, and were not anthropogenically disturbed. It was determined that these lake characteristics were necessary to adequately assess the rate of change in acidification in sensitive northeastern lakes. The DDRP project also assessed streams in the mid-Appalachian and southern Blue Ridge regions; these waterbodies are also subsets of the larger NSWS set.

The purpose of the MAGIC model is to calculate the rate and extent of recovery from acidification, so “DDRP waterbodies” are used to calibrate the model. The MAGIC estimate of acidification presented in this NAPAP Report for the Adirondacks, Northeast, and Southeast represents a reasonable scientific estimate of the current regional extent of acidification in acid-sensitive lakes and streams in the Eastern U.S. and the projected future conditions of those waterbodies on a regional scale.



FIGURE 32. Projected change in the number of chronically acidic lakes and streams in 2030 with and without Title IV



Note: The area of the Northeast modeled by MAGIC includes Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York (including the Adirondacks), and northeastern Pennsylvania. The Southeast includes the rest of Pennsylvania, the mountainous areas of Virginia and Maryland, eastern West Virginia, southwestern North Carolina, east Tennessee, and northern Georgia.

Source: EPA

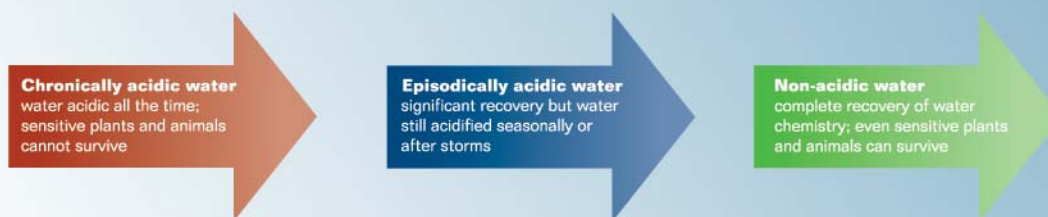
As indicated on page 57, these projections do not include emission reductions as a result of CAIR, any mobile source regulations, or any state regulations finalized after April 2003.

Adirondacks and streams in Virginia no longer support populations of fish.^{30, 165} Unlike the response of air quality and deposition to changes in emissions, lakes and streams take years to decades to fully reflect reductions in acid deposition. In some cases soil chemistry has been significantly altered, and ions must either build up (i.e. base cations) or be leached out (i.e. sulfate and/or nitrate) before the chemistry can return to its pre-acidification status. In addition, algae, zooplankton, and fish communities take time to rebuild their food webs, or, in some cases, to migrate back into areas where they have become completely absent due to acidification. Therefore, lake and stream conditions in 2010 reflect only a small part of the recovery that is expected due to Title IV. The full impacts of Title IV are not expected to be

seen in the Northeastern U.S., including in the Adirondacks, for several decades after emission reductions begin.³⁰ Streams in the Southeast, because of their soil chemistry, are expected to take even longer.¹⁰³ Lake and stream quality in 2010 would represent only a small portion of the recovery expected due to Title IV. Therefore, lake and stream conditions are presented for 2030 and reflect emission reductions that occurred between 1990 and 2010.

Modeling conducted with the MAGIC model indicates that, by 2030, the percentage of chronically acidic lakes in the Adirondacks is expected to be 12%, down from 33% in 1984 (see Figure 32). The percentage of non-acidic lakes is expected to remain constant at 36%. In the Northeast, the percentage of chronically acidic lakes is expected to be 6%, down from 13% in 1984. The percentage of non-acidic lakes is expected to be 69%, up from 67% in 1984. The percentage of episodically acidic lakes in both the Adirondacks and the Northeast as a whole actually grows

FIGURE 33. Stages of recovery for acidic lakes and streams



Note: See Chapters 2 and 3 for a full discussion of the ecological effects of chronic and episodic acidification
Source: EPA

in this stage of recovery. This is because more chronically acidic lakes become episodically acidic than episodically acidic lakes become non-acidic (see Figure 33). While chronically acidic lakes are most affected by acidification, episodically acidic lakes are also ecosystems that are significantly impaired by acid deposition and biological endpoints (i.e. sensitive fish species) remain susceptible.

In the Southeast, because of the type of soils in the region, emission reductions are expected only to slow the rate of acidification in acid-sensitive streams. In 2030, the percentage of chronically acidic streams in the Southeast is expected to be 17%, up from 8% in 1985 (the southeastern streams were assessed the year after the northeastern lakes) (see Figure 32). The percentage of non-acidic streams is expected to be 56%, down from 73% in 1985. This is not because Title IV has had no effect in the Southeast; on the contrary, as indicated in Figure 32, there would be many more chronically acidic streams in 2030 if Title IV were not being implemented. The unglaciated (often sand or clay) soils in the Southeast have absorbed a large amount of acid deposition already and, because of their composition, are expected to continue releasing it into waters in the region for many decades. This lag time, which is much longer than the lag time seen in northern glaciated (often granite) soils, means that the streams are still showing the effects of historic emissions and will not show the full effects of emission reductions for many decades.¹⁰³

Human Health

SO₂ and NO_x emissions react in the atmosphere to form fine particles and ozone. These gases and fine particles are associated with a number of significant health effects in sensitive populations. While high SO₂ concentrations can result in temporary breathing impairments in sensitive people, including asthmatics and those who are active outdoors, most of the health effects are due to fine particles.

A large number of epidemiological studies over the past 10 to 20 years show an association between ambient fine particle concentrations (e.g. sulfates and nitrates formed in the atmosphere from SO₂ and NO_x emissions) and health effects, such as increased numbers of hospital admissions and emergency room visits for heart and lung disease, increased incidences of respiratory disease and symptoms (such as asthma), decreased lung function, and even premature death. Children, the elderly, and individuals with existing cardiovascular or lung conditions, such as asthma, are especially vulnerable to the effects of particles.¹⁵ Title IV has reduced the amount of fine particles in the air (see Figures 16–20) by lowering SO₂ and NO_x emissions, achieving significant

human health benefits nationwide long before emissions drop to the level of the cap. It is expected that Title IV will achieve further benefits as SO₂ emissions continue to decrease to the level of the emissions cap.

NO_x emissions react with volatile organic compound gases in the atmosphere in the presence of sunlight to form ozone. The scientific literature shows associations between ozone and a number of effects on the respiratory system, including aggravation of asthma, increased susceptibility to respiratory illnesses like pneumonia and bronchitis, and permanent lung damage. Children, the elderly, and people with existing respiratory problems are most vulnerable to the health effects of ozone. Those exercising or working outside during the ozone season (May–September) tend to have the highest exposures to ozone. Health benefits have been achieved under Title IV due to NO_x reductions not only because NO_x contributes to the formation of fine particles but also because reducing NO_x emissions reduces ozone concentrations.

The value of Title IV's health benefits has been estimated by several organizations and analysts since its passage in 1990.^{166–171} In each case, these analyses found that the quantified health benefits of Title IV are very substantial. For example, in their most recent analysis, OMB estimates that the annual health benefits of Title IV in 2010 will be \$79 billion to \$83 billion (\$2001). Title IV's SO₂ reductions account for \$78 to \$79

billion of this total, and Title IV's Phase II NO_x reductions account for an additional \$1 to \$5 billion.¹⁷¹ These benefits include only the benefits of avoiding premature mortality due to air pollution. Title IV has provided additional benefits as well, that are not included in this most recent monetized estimate from OMB, including reductions in the number of non-fatal heart attacks, cases of acute and chronic bronchitis, emergency room visits, asthma attacks, and days lost from work and school. As with other benefits analyses, the benefits estimates are subject to uncertainties such as those associated with estimates of future-year emissions and air quality and uncertainties in the estimated relationships between changes in pollutant concentrations and resulting changes in health effects.

Other Benefits of Title IV

In addition to the reduced acidification and human health benefits of Title IV, there are other, un-quantified, benefits of full implementation of Title IV. These benefits from reductions in sulfur deposition and sulfate and nitrate concentrations include healthier forests, less erosion of buildings, monuments, and other historic structures, and improved visibility. These benefits occur throughout the Eastern U.S. in national parks and wilderness areas, cities and urban areas, and in rural areas. The reductions in nitrogen deposition, while not extensive, are expected to benefit nitrogen-sensitive coastal waters along the eastern and gulf coasts as well. For more information on the environmental effects of acid deposition see Chapters 2 and 3. Acidification of lakes has been linked in some areas to higher levels of mercury contamination in fish; reductions in the acidity of these lakes may help reduce levels of mercury contamination in fish.^{172, 173} Finally, these environmental benefits can result in economic benefits by helping to preserve natural resources critical to industries such as forestry and fishing and increasing the amount of tourism, as well as improving the overall quality of life in areas where ecosystems have suffered from acidification.



Chapter 5: Beyond Title IV: Ecological Impacts of Further Emission Reductions

A broad consensus of scientists studying acid deposition and ecosystem recovery have published reports since publication of the last NAPAP report (1996) indicating that further emission reductions beyond those achieved by Title IV are necessary to allow sensitive forests and aquatic ecosystems to recover from acidification. The SO₂ and NO_x emission reductions achieved under Title IV from the power sector are now recognized as insufficient to achieve recovery or to prevent further acidification in some regions. Further reductions in SO₂ and NO_x emissions from the power generation sector would reduce the amount of acidic deposition in sensitive ecosystems and result in healthier forests and fewer acidic lakes and streams; however, even elimination of SO₂ emissions from power plants will not fully protect all acid-sensitive ecosystems.

Title IX of the 1990 Clean Air Act Amendments requires NAPAP to report quadrennially on “the reduction in deposition rates that must be achieved in order to prevent adverse ecological effects” (Public Law 101-549-Nov. 15, 1990). Deposition levels that correlate with a “threshold” of adversity are scientifically complex and difficult to establish. NAPAP’s 1990 *State of Science and Technology Report No. 13* states that “biological responses to changes in acid-base chemistry occur along a continuum. There is not a single value or set of chemical concentrations that represents a ‘threshold’ for ‘significant adverse biological effects’”¹⁷² In addition, some lakes and streams are naturally acidic and experience “adverse ecological effects” in the form of reduced fish populations or other impacts due to the presence of organic acids. Therefore, NAPAP determined that the logical path was to describe the ecosystem responses along a continuum, thereby allowing decision makers to determine the level of acceptable risk.¹⁷⁴

NAPAP presented a working definition of “adverse ecological effects” in the 1996 NAPAP Report to Congress based on the intent of Congress, as expressed in the 1990 Clean Air Act Amendments and shaped by other relevant environmental statutes (Comprehensive Environmental Response, Compensation and Liability Act and the Clean Water Act) and associated regulations. The definition is:

Adverse ecological effects: any injury (i.e., loss of chemical or physical quality or viability), to any ecological or

ecosystem component, up to and including at the regional level, over both long- and short-terms.

Adverse impacts to ecological processes or ecosystem components include reductions in acid neutralizing capacity and increasing aluminum concentrations in a lake or stream, leading to loss of fish and other biota; loss of important nutrients such as calcium, from forest soils; and, increased susceptibility of trees to pests, disease, and winter temperatures, leading to decreasing forest productivity and forest dieback.

Adverse ecological impacts also include the effects of nitrogen saturation in forests, coastal eutrophication as a result of atmospheric deposition, and injury to plants as a result of ozone exposure. Other areas addressed by NAPAP (i.e., materials, visibility, and human health) would follow the same definition, but are not considered here as ecological effects.²⁹ This NAPAP Report is based on that definition of adverse ecological effects and uses the same approach of investigating ecosystem responses along a continuum. The report focuses on “recovery” as indicated by changes in water chemistry (i.e. chronically acidic, episodically acidic, and non-acidic lakes and streams).

While the definition of a “threshold” is complex, there has been a significant amount of research in the past decade indicating that ecosystems continue to be affected by acid deposition. The 1995 *Acid Deposition Standard Feasibility Study* concluded that, for the near term, sulfur deposition was likely to remain the primary source of acidification in most sensitive areas of eastern North America. However, as SO₂ emissions decrease, the importance of nitrogen increases in relation to both short-term and long-term acidification. The Nitrogen Bounding Study (NBS), the primary component of the



Acid Deposition Standard Feasibility Study, demonstrated that, at certain times and under certain deposition scenarios, sulfur and nitrogen could have approximately equal roles in surface water acidification. In addition, the NBS concluded that in regions where nitrogen deposition is or could become a more direct cause of chronically acidic lakes and streams, further limits on nitrogen deposition could produce dual benefits by reducing acid deposition rates and lengthening times to watershed nitrogen saturation. Based on model projections, EPA's report concluded that further reductions of 40–50% beyond Title IV SO₂ and NO_x emissions may be necessary to fully protect the most sensitive lakes and streams.¹⁷⁵

Two national expert workshops organized by the Ecological Society of America reached similar conclusions regarding the effects of nitrogen and sulfur deposition. A June 1997 workshop on atmospheric nitrogen deposition to coastal watersheds found that increasing supplies of nitrogen have resulted in a range of ecological impacts, including an increased incidence of harmful algae blooms and fish kills, reducing the number of acres covered with submerged aquatic vegetation (SAV), and changes to the fundamental ecological structure of some coastal waters.¹⁷⁶ A March 1999 workshop of acid rain experts focused on ecological response and recovery from sulfur and nitrogen emissions and deposition. The workshop report highlighted the importance of nitrogen deposition as a cause of acidification and found that ecological recovery has yet to occur in many regions. The workshop concluded that further SO₂ emission reductions beyond Title IV may be necessary to achieve ecological recovery in lakes and streams affected by acid deposition.¹⁷⁷

In the period since the 1996 NAPAP report release, various studies focused on specific regions of the country have shed new light on the regional impacts of sulfur and nitrogen deposition. These more recent analyses considered reductions greater than those suggested in EPA's 1995 report. For example, a regional survey of streams in the southern Appalachian region found that 65%

of sampled locations demonstrate moderate to severe depletion of fish communities, some portion of which is attributable to acidification.¹⁰⁷ Studies of trout streams in the Virginia part of that region document the first loss of a fish population in the Shenandoah National Park due to acidification.⁴⁶ Researchers in the southern Appalachian region conclude that streams in this region are still threatened by acid deposition. Based on model projections they conclude that further reductions of sulfate deposition beyond levels achieved by the Title IV SO₂ emission reductions are necessary to prevent further acidification of Virginia brook trout streams.⁴⁶ A recent regional assessment completed by the Southern Appalachian Mountain Initiative (SAMI) concluded that local and regional power generation sources must reduce SO₂ emissions by at least 70% and NO_x emissions by at least 67% from 2000 levels in order to decrease stream acidification and reduce forest ecosystem damage due to nitrogen deposition in high elevation forests.¹⁷⁸

Two major assessments of acid deposition and its effects in the Northeast reached similar conclusions. Driscoll et al. (2001) found that full implementation of the 1990 CAAA will not result in substantial recovery in northeastern lakes and streams impacted by acid deposition. Based on model projections, the study concluded that reductions of SO₂ emissions from power generation of up to 80% beyond Title IV requirements were necessary for currently-acidic streams in the Northeast to become non-acidic.³⁰ Driscoll et al. 2003 considered the impact of nitrogen deposition on forests, lakes, and streams in the Northeast. The study found that reduction in NO_x emissions from power generation of 75%, combined with mobile source reductions, are necessary to arrest acidification of forest soils, lakes, and streams in that region.³⁸

Finally, additional recent studies demonstrate symptoms of nitrogen saturation in many ecosystems across the country,⁵¹ including several areas in the Western U.S.¹³³ For example, high-altitude watersheds of the Colorado Front Range exhibit symptoms of advanced stages of nitrogen excess.⁴⁴ A 1995 survey of 91 high-elevation lakes in the central Rockies found changes in water quality caused by increasing amounts of inorganic nitrogen deposition, and intensive sampling at a smaller number of sites demonstrated that increasing wet nitrogen deposition is causing episodic acidification in headwater catchments of the Green Lakes Valley in the Colorado Front Range.⁴² These results are significant since increases in atmospheric nitrogen deposition can lead to ecosystem changes in this region,⁴⁰ including lake eutrophication and altered ecosystem composition in both lake and alpine meadow environments.¹³³ While greater uncertainty exists, nitrogen deposition in the West also has been linked to enhanced growth of invasive species, delete-



rious impacts on threatened and endangered species, and alterations of the fire cycle.¹³³

An additional examination of the literature surrounding the effects of atmospheric deposition is included in the Regulatory Impact Analysis in support of the 2005 Clean Air Interstate Rule (CAIR). This analysis can be found on the internet at www.epa.gov/interstateairquality/pdfs/finaltech08.pdf

In response to the Congressional request to identify the deposition rates that would prevent any adverse ecological effects, NAPAP has analyzed several emission reduction scenarios that broadly bound the range of reductions presented in the post-1996 literature cited above. These results provide an indication of the environmental improvements that would be expected from additional emission reductions from both Title IV and non-Title IV sources. These environmental improvements do not necessarily constitute recovery of acid-sensitive forests, lakes, and/or streams that have been impaired by acid deposition (see Figure 1 for the location of acid-sensitive areas). They do, however, provide an indication of the scope and magnitude of the impact of emission reductions on deposition levels and impact on acid-sensitive ecosystems. Other sensitive ecosystems, such as estuaries and coastal waters, would also benefit from reductions in nitrogen deposition, but are not analyzed here. The information requested by Congress and presented here represents part of what is needed when determining appropriate future actions; other information includes the costs and other impacts of emission reductions from the power sector or any other sectors and the value the public places on further improvements to the environment and human health.

Analysis of the Environmental Impact of Further Air Emission Reductions

SCENARIOS ANALYZED

This modeling, conducted by EPA, analyzed several scenarios representing emission changes from stationary sources. The results are presented for sulfur and nitrogen deposition because these pollutants are the primary components of acid deposition. This NAPAP analysis focuses on reductions from power plants; other sources also emit pollutants that contribute to acid deposition. Notably, sources outside the power generation sector are projected to emit approximately 45% of the SO₂ and 75% of the NO_x emitted in 2020 under the Base Case scenario.¹⁷⁹

Three sensitivity scenarios estimating various levels of additional reductions are compared to a Base Case projecting emissions with full implementation of already-promulgated

Clean Air Act programs in 2000 (Title IV, the NO_x SIP call, and Tier II and Heavy Duty Diesel SO₂ and NO_x reductions that are projected to take effect by 2010). The scenarios were modeled using a cap and trade mechanism for both SO₂ and NO_x (reducing the SO₂ cap under Title IV and imposing an annual cap for NO_x). The reductions identified below for each scenario represent cap levels for each pollutant in 2020. The projected emissions used for the air quality modeling in 2020 are somewhat higher than the cap levels for all scenarios as a result of the early reductions and allowance banking predicted by the emissions model (IPM). Additional details on the scenarios are presented below.

- **Base Case (2020):** This scenario does not include rules that were finalized after the spring of 2001 (including CAIR, CAMR, and BART), new or anticipated actions under the Clean Air Act, including the Non-Road Diesel Rule, or other emission reductions that would be necessary to attain and maintain the fine particle and ozone NAAQS for which states are required to submit implementation plans by 2007, or to achieve regional haze reduction goals.
- **Scenario A:** This scenario includes an additional 60% reduction in SO₂ emissions from the power generation sector beyond the cap of 8.95 million tons required under Title IV (a cap of 3.58 million tons/year of emissions in 2020). It also includes national annual NO_x emission reductions from the power generation sector of 68% beyond Title IV levels (a cap of 1.87 million ton/year of emissions in 2020, or an emission rate of 0.15 lbs/mm BTU).
- **Scenario B:** This scenario includes an additional 75% reduction in SO₂ emissions from the power generation sector beyond the cap of 8.95 million tons required under Title IV (a cap of 2.25 million tons/year of emissions in 2020). It also includes national annual NO_x emission reductions from the power generation sector of 80% beyond Title IV levels (a cap of 1.25 million ton/year of emissions in 2020, or an emission rate of 0.10 lbs/mm BTU).



- **Scenario C:** This scenario is roughly equivalent, in terms of tons of SO₂ reduced, to elimination of SO₂ emissions from the power generation sector. It includes an additional 90% reduction in SO₂ emissions from the power generation sector beyond the cap of 8.95 million tons required under Title IV (a cap of 1 million tons/year of emissions in 2020) and a 50% reduction in SO₂ emissions from non-power generation sources (e.g., industrial boilers).^{*} The scenario also includes national annual NO_x emission reductions of approximately 80% beyond Title IV levels (a cap of 1.25 million ton/year of emissions in 2020, or an emission rate of 0.10 lbs/mm BTU).

The magnitude of emission reductions influences both the amount of recovery from acidification that takes place and the rate at which recovery happens. The rate of recovery is also influenced by the geological and ecological characteristics of the lakes and/or streams in the area. Lake conditions in the Adirondacks and Northeast and stream conditions in the Southeast were modeled using the MAGIC model (see page 53 for a description of MAGIC). These regions were chosen because they are among the most acid-sensitive ecosystems and are downwind of many of the emission sources affected by the Acid Rain Program (see Figure 1). Emissions under Scenarios A, B, and C were assumed to be held constant after 2020; emissions under the Base Case continued to decrease slightly after 2020 until 2030. Projected lake and stream conditions were compared to modeled estimates of lake and stream conditions in 1984/1985. Since lake and stream quality in 2020 would represent only a small portion of the recovery expected due to the scenarios analyzed, lake and stream conditions are presented for 2030. Regional predictive models of the ecological responses in forests to changes in emissions or deposition are not currently available and were not modeled in this assessment. This report employs models and analytical tools that are widely used and peer-reviewed. As

WHAT WILL AIR QUALITY BE LIKE IN 2020?

Similar to the analysis presented in Chapter 4, the scenarios modeled here by NAPAP are based on emissions changes expected from programs that affect the power industry that were already "on the books" when the modeling was conducted (2002–2003). While this projection includes an appropriate perspective from which to compare scenarios, recent EPA regulatory actions will yield substantial additional SO₂ and NO_x emission reductions. For example, implementation of CAIR in 2020 is expected to reduce SO₂ emissions to 6.1 million tons annually nationwide (3.3 million tons in the Eastern U.S.), an approximately 60% reduction from 2003 emissions levels (approximately 65% in the Eastern U.S.). Similarly, nationwide NO_x emissions from power plants are expected to be 2.2 million tons annually in 2009, (1.3 million tons in the Eastern U.S.), an approximately 50% reduction from 2003 levels (approximately 60% reduction in the Eastern U.S.). Additional reductions from State actions to meet fine particle and ozone SIP requirements, as well as reductions required under the Clean Air Visibility Rule, are expected to result in additional reductions in emissions of SO₂ and NO_x. As a result, actual emissions will be substantially lower than the emission levels incorporated in the base case.

with any detailed analysis of complex scenarios, the results presented in this report are subject to uncertainties concerning emissions estimates, air quality modeling and deposition projections, and the impact of emission reductions on ecological systems.

CHANGES IN ACID DEPOSITION

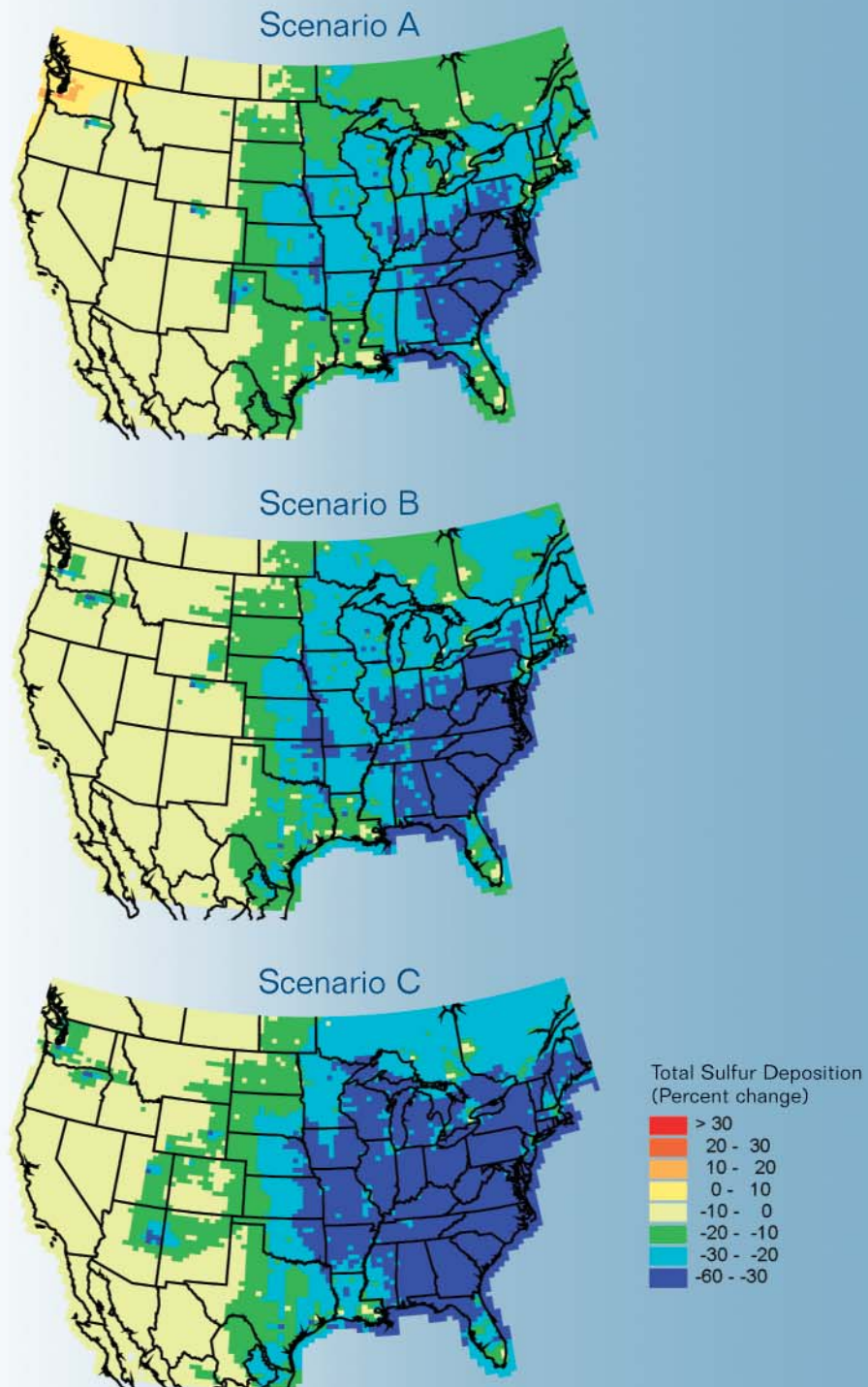
Even with Title IV in place, lakes and streams in many parts of the U.S. are still experiencing acidification due to sulfur and nitrogen deposition. This is especially prevalent in the East, where sulfur deposition is currently approximately 15–25 kg/ha/year. Sulfur deposition levels in the West are much lower, generally less than 10 kg/ha/year. Inorganic nitrogen deposition is currently approximately 3–7 kg/ha/year in the East. Inorganic nitrogen deposition levels in the West, although in some areas still high enough to cause ecological damage, are lower, on the order of less than 4 kg/ha/year.

Acid deposition in sensitive ecosystems alters soils, stresses forest vegetation, acidifies lakes and streams, and harms fish and other aquatic life. For example, 24% of Adirondack lakes with low pH and ANC levels surveyed in

^{*} The SO₂ emission reductions included from non-power generation sources is approximately 2 million tons, almost twice the remaining SO₂ emissions from the power generation sector once the level of the cap is reached.



FIGURE 34. Projected percent change in annual sulfur deposition from base case in 2020 with additional SO₂ and NO_x emission reductions



Source: EPA

the mid-1980s did not support fish, and 6% of Virginia trout streams studied in the late 1990s were unable to support brook trout or other fish species due to chronic acidity.^{30, 165} While some Adirondack lakes have always been acidic due to the presence of organic acids, data collected in the 1980s indicates that the vast majority of those larger than 4 hectares and almost all streams in the Southeast were acidic due to atmospheric deposition.³¹ Recent research on forest ecosystems shows that acid deposition has contributed to the decline of red spruce throughout the Eastern U.S. and may have contributed to the decline of sugar maple trees in central and western Pennsylvania.³⁰ Overall, the effects of acid deposition can interfere with valuable ecosystem benefits, such as forest productivity and water quality.

CHANGES IN SULFUR DEPOSITION

All additional reduction scenarios modeled in this analysis are projected to lead to significant regional reductions in sulfur deposition as compared to projected conditions under the Base Case in 2010 (Figure 34). Under Scenario A, reductions in deposition of 10–30% would be found from the Plains states east to the Atlantic seaboard, with reductions of 30–60% in the southeastern states stretching up into Pennsylvania and southeastern Ohio. Most western states, from the Rocky Mountains west, would see reductions in deposition of up to 10%.

Scenario B extends the area of largest reduction in sulfur deposition northwards and westwards. Scenario C would extend the area with the greatest reductions in sulfur deposition northward to Maine and across the Mississippi River into the eastern portion of the Plains states. For example, under Scenario B, the Adirondacks, mid-Appalachians, and southern Blue Ridge Regions would all experience reductions in sulfur deposition of up to 60%. Scenario C would expand those reductions into other acid sensitive areas, including Northern New England and the Upper Midwest. These reductions are expected to provide ecological benefits to these acid-sensitive

regions, but are not expected to solve all ecological problems related to acid deposition in those areas.

CHANGES IN NITROGEN DEPOSITION

As mentioned above, acidification prevents lakes and streams from supporting fish and other aquatic life. In addition, many estuaries and forests are being affected by excessive loading of nitrogen, including atmospheric deposition of nitrogen. Modeling of the Base Case indicates that, in 2020, Title IV, the NO_x SIP call, and the Tier II and Heavy Duty Diesel mobile source rules are expected to achieve reductions in nitrogen deposition of greater than 30% from North Carolina north along the Atlantic seaboard to Maine. Large portions of the rest of the Eastern U.S. will experience reductions in nitrogen deposition of 10–20% due to existing programs. Large portions of the Western U.S. will also achieve significant reductions in deposition of 10–20% or more due to existing mobile source reductions. These reductions in deposition will take place in some of the areas experiencing the most damage from nitrogen deposition, including the Adirondacks, Appalachians, Colorado Front Range, and the San Bernadino Mountains.

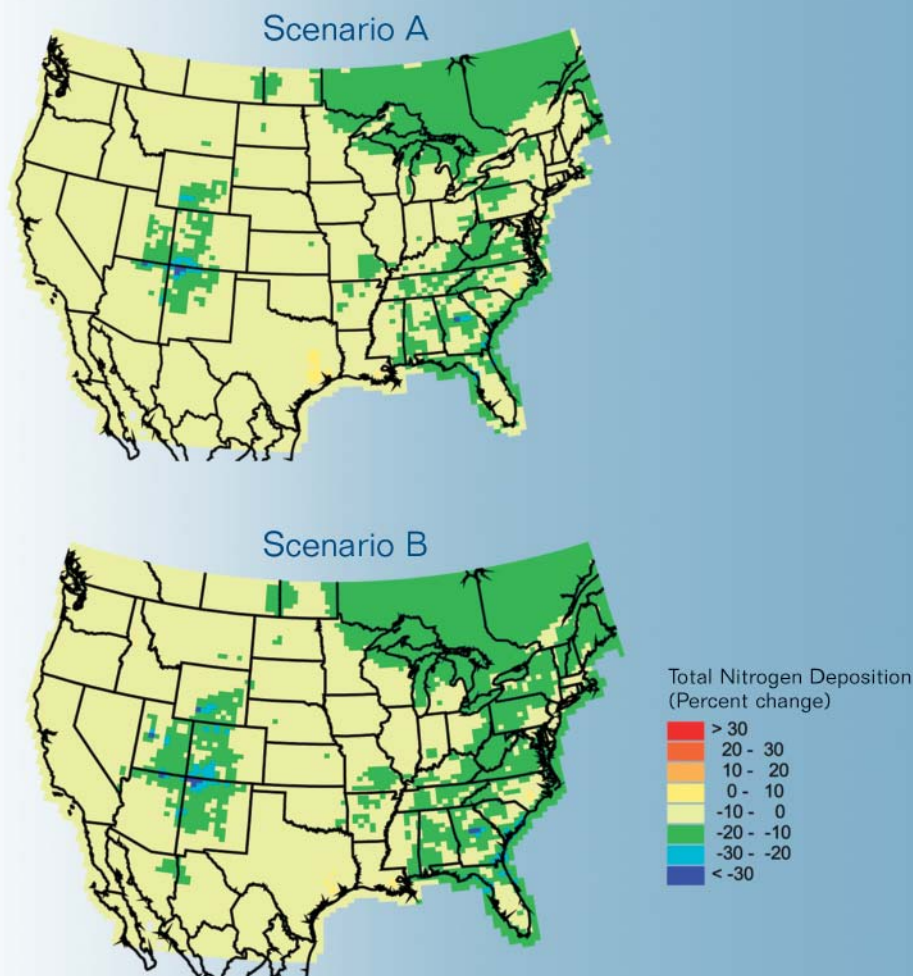
The emission reductions from power plants in the scenarios modeled in this analysis are projected to lead to additional regional reductions in nitrogen deposition as compared to projected conditions in 2020 under the Base Case (Figure 35). Under Scenario A, there would be additional reductions in nitrogen deposition of 10–20% beyond the levels seen under the Base Case in patches throughout the Eastern U.S. Similar levels of emission reductions would be found in the Four Corners region of the West. The model suggests a slight increase in deposition in east Texas, southern Louisiana, and eastern North Carolina due to increased utilization of units (these units are meeting their NO_x limits under Title IV). The rest of the country would see additional reductions in deposition of up to 10%.

Scenario B would expand the area of 10–20% reduction in deposition from the Base Case to cover more of the eastern seaboard, Colorado, New Mexico, and Utah. It would reduce the area receiving slightly increased levels of nitrogen deposition in Texas, but not eliminate it.

These emission reductions would also lead to significant additional reductions in nitrogen deposition compared to the Base Case in sensitive ecosystems still experiencing water quality and/or forest health problems due to acidification. For example, the Adirondacks would receive a 10–20% reduction in deposition as compared to the Base Case under Scenario B and the Chesapeake Bay watershed would receive an approximately 10% reduction in deposition as compared to the Base Case under Scenario B. A sensitive



FIGURE 35. Projected percent change in annual nitrogen deposition from base case in 2020 with additional SO₂ and NO_x emission reductions

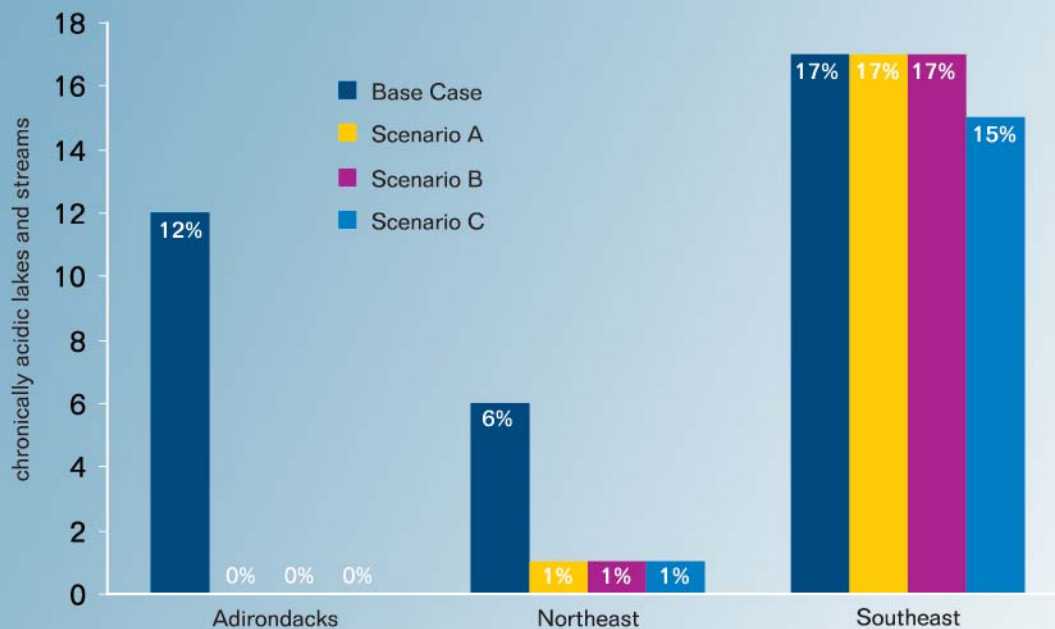


Source: EPA

ecosystem thought to be in danger of experiencing excessive nitrogen loading, the Colorado Front Range, would receive approximately a 20% reduction in 2020, with reductions in some areas over 30%, as compared to the Base Case scenario under Scenario B. As is the case with reductions in sulfur deposition, these reductions are expected to provide ecological benefits in many sensitive ecosystems, but some problems due to nitrogen deposition are expected to remain.

NO_x emissions are the same in Scenario B and C so nitrogen deposition was not modeled for Scenario C. Although the nonlinearities involved in particulate chemistry indicate that there would be some change in nitrogen deposition based on changes in sulfur emissions, Scenario C is expected to show few significant differences in nitrogen deposition compared to Scenario B.

FIGURE 36. Change in the number of chronically acidic lakes and streams in 2030 with additional SO₂ and NO_x emission reductions



Note: The area of the Northeast modeled by MAGIC includes Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York (including the Adirondacks), and northeastern Pennsylvania. The Southeast includes Appalachian mountain streams in the rest of Pennsylvania, western Virginia, western Maryland, eastern West Virginia, southwestern North Carolina, eastern Tennessee, and northern Georgia.

Source: EPA

The amount of acidification projected in the Base Case does not include emission reductions as a result of CAIR or CAMR, any mobile source regulations, or any state regulations finalized after April 2003.

WATER QUALITY

Acid deposition affects water quality in sensitive ecosystems by acidifying lakes and streams, changing water chemistry, and altering soil chemistry. For example, 24% of Adirondack lakes with low pH and ANC levels surveyed in the mid-1980s did not support sensitive fish, and 6% of Virginia trout streams studied in the late 1990s were unable to support brook trout or other fish species due to chronic acidity.^{30, 165} Currently available modeling tools allow researchers to estimate the effects of reductions in acid deposition on several aspects of the water chemistry of lakes and streams. The effects of acid deposition on the other ecosystem components, such as soil chemistry,

zooplankton or fish health, or forest vegetation cannot at this point be identified quantitatively on a regional basis.

Watershed characteristics (e.g., soils, bedrock type, geologic history) affect the rate of water chemistry response to acid deposition. "Direct response" lakes or streams manifest changes relatively quickly in response to changes in deposition, whereas "delayed response" lakes or streams manifest changes over a longer period of time.

The implementation of the Base Case is expected to significantly reduce the percentage of chronically-acidic streams in all three areas beyond what would have occurred without Title IV (see Chapter 4 for a detailed discussion of the water quality improvements expected from full implementation of Title IV and for a discussion of the population of lakes and streams considered in this assessment). This reduction in the number of acidic lakes and streams, as well as reductions in the frequency and/or



severity of acidification in the remaining acidic lakes and streams, improves the health of fish populations and other acid-sensitive species. However, as shown in the base case modeling presented in Figure 36, Title IV will not eliminate the problem of acidic waters. Chronically acidic waters are projected to remain in both the Northeast and the Southeast and some waters in all three of the acid-sensitive regions modeled in this analysis are expected to continue to experience episodic acidification.

The changes in water quality for the three additional reduction scenarios were also modeled in this analysis. While the effects of additional emission reductions differ by region, the amount of reductions makes little difference in the resulting chronic acidity of any one region. However, the larger the emission reductions, the more “non-acidic” lakes and streams are projected (See Figure 22 for an explanation of the stages of recovery from acidification).

Modeling results indicate that the additional 60% reduction in SO₂ emissions from power generation beyond Title IV would result in the virtual elimination of chronic acidity from lakes in the Northeast, including the Adirondack Mountains, by 2030 (Figure 36). Research indicates that larger reductions in deposition would speed the time to recovery of those Northeastern lakes.³⁰ Only under Scenario C would the percentage of episodically acidic lakes also begin to decrease.

The story is somewhat different for the Southeast (Figure 36). Due to the unique geology of the area, including its porous sandy soils, southeastern streams respond very slowly to reductions in acid deposition (characterized as “delayed response”). As a result, no additional recovery is expected in chronically acidic streams in the Southeast, even with reductions beyond the base case included in Scenarios A and B. According to model projections, a reduction of more than 75% in SO₂ emissions from power generation sources would not reduce the number of chronically acidic streams in the Southeast. This level of emission reductions from the power generation sector would slow the rate of acidification of these waters, but improvement (i.e., a reduction in the number of chronically acidic streams) is projected to begin only after larger reductions and/or reductions from other source categories such as those associated with Scenario C occur.

Summary

Title IV has been quite successful at effectively reducing emissions of SO₂ and NO_x from power generation to the levels set by Congress. In fact, by 2020 emissions from power plants are expected to be less than half of the total SO₂ emissions in the U.S. As a result of these emission reductions, some acid-sensitive areas are already beginning to show signs of recovery. Full implementation of Title IV, and the passage of time needed for affected ecosystems to respond to the new environmental conditions, are expected to allow more areas to recover. However, several scientific studies indicate that the emission reductions achieved by Title IV are not sufficient to allow recovery of acid-sensitive ecosystems. Estimates from the literature of the scope of additional emission reductions that are necessary in order to protect acid-sensitive ecosystems range from approximately 40–80% beyond full implementation of Title IV, with the most recent studies focusing on the largest reductions. This report analyzes the impacts of a range of levels that would achieve fuller environmental recovery from acid rain and greater avoidance of the adverse ecological effects associated with acid deposition.

The results of the modeling presented in this Report to Congress indicate that broader recovery is not predicted without additional emission reductions. Elimination of all SO₂ emissions from power plants, however, will not fully protect all acid-sensitive ecosystems affected by acid deposition; reductions from other source categories would be needed. The information requested by Congress and presented here represents part of what is needed when determining appropriate future actions; other information includes the costs and other impacts of emission reductions and the value the public places on further improvements to the environment and human health.



References

- ¹ Ellerman, A.D. 2003. Lessons from Phase II compliance with the U.S. Acid Rain Program. Massachusetts Institute of Technology. Center for Energy and Environmental Policy Research, 03-009 WP.
- ² Burtraw, D. 2000. Innovation Under the Tradable Sulfur Dioxide Emission Permits Program in the U.S. Electricity Sector. Resources for the Future Discussion Paper 00-38.
- ³ Environmental Defense. 2000. From Obstacle to Opportunity: how acid rain emissions trading is delivering cleaner air. *Environmental Defense*, New York, NY.
- ⁴ Ellerman, A.D. 2002. Ex Post Evaluation of Tradable Permits: The U.S. SO₂ Cap-and-Trade Program, prepared as a case study report under the program for the Ex Post Evaluation of Tradable Permits: Methodological and Policy Issues being conducted by the National Policies Division of the Environmental Directorate of the OECD.
- ⁵ Ellerman, A.D., P.L. Joskow, R. Schmalensee, J.P. Montero, and E.M. Bailey, 2000. *Markets for Clean Air*. Cambridge University Press, New York, NY.
- ⁶ Burtraw, Dallas. 1996. Cost Savings Sans Allowance Trades? Evaluating the SO₂ Emission Trading Program to Date. Discussion Paper 95-30-REV February 1996.
- ⁷ ICF Resources, Incorporated. 1989. Economic Analysis of Title V (Acid Rain Provisions) of the Administration's Proposed Clean Air Act Amendments (H.R. 3030/S. 1490). Based on "Flexible" Implementation case in Tables A1, A5, B1, and B5, plus mid-point estimate for banking from page 24.
- ⁸ EPRI. 1993. Integrated Analysis of Fuel, Technology and Emission Allowance Markets: Electric Utility Responses to the Clean Air Act Amendments of 1990. Electric Power Research Institute, Palo Alto, CA. Table C-1, TR-102510.
- ⁹ Carlson, C., D. Burtraw, M. Cooper, and K.L. Palmer. 2000. Sulfur Dioxide Control by Electric Utilities: What Are the Gains from Trade? In *Journal of Political Economy*: 2000, vol.108, no.6, pp1292-1326.
- ¹⁰ GAO. 1994. Allowance Trading Offers an Opportunity to Reduce Emissions at Less Cost. U.S. General Accounting Office, Washington, DC pp. 36, 74.
- ¹¹ Ellerman, A.D. and J.P. Montero. 2002. The Temporal Efficiency of SO₂ Emissions Trading. MIT-CEEPR Working Paper 02-003.
- ¹² McLean, B.J. 1996. The Sulfur Dioxide (SO₂) Allowance Trading Program: The First Five Years. U.S. Environmental Protection Agency, Washington, DC.
- ¹³ Kruger, J. and M. Dean. 1997. Looking back on SO₂ trading: What's good for the environment is good for the market. *Public Utilities Reports*, 135 (15) August 1, 1997.
- ¹⁴ U.S. EPA. 2002b. 40 CFR Part 75 (Continuous Emission Monitoring. U.S. Government Printing Office, Washington, DC.
- ¹⁵ U.S. EPA. 2003. Air quality for particulate matter (Fourth External Review Draft). Office of Research & Development. Research Triangle Park, NC. June 2003.
- ¹⁶ U.S. EPA. 2002. Acid Rain Program: Annual Progress Report, 2001. U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-02-009.

- ¹⁷ Swift, B. 2000. Allowance Trading and Potential Hot Spots: good news from the Acid Rain Program. *Environmental Law Institute Environment Reporter* 31: 954-959.
- ¹⁸ Holland, D.M., P. Carega, and R.L. Smith. 2004. Regional Trends in Rural Sulfur Concentrations. *Atmospheric Environment* 38 pp 1673-1684.
- ¹⁹ Hicks, B.B., T.P. Meyers, R.P. Hosker Jr., and R.S. Artz. 2001. Climatological features of regional surface air quality from the Atmospheric Integrated Research Monitoring Network (AIRMoN) in the USA. *Atmospheric Environment* 35: 1053-1068.
- ²⁰ U.S. EPA. 2000. National Air Pollutant Emission Trends, 1990-1998. EPA-454-R-00-002.
- ²¹ Baumgardner, R.E., Jr., T.F. Lavery, C.M. Rogers, and S.S. Isil. 2002. Estimates of the Atmospheric Deposition of Sulfur and Nitrogen Species: Clean Air Status and Trends Network, 1990-2000. *Environmental Science and Technology* 36: 2614-2629.
- ²² Butler Thomas J., Gene E. Likens, and Barbara J.B. Stunder. 2001. Regional-scale impacts of Phase I of the Clean Air Act Amendments in the USA: the relation between emissions and concentrations, both wet and dry. *Atmospheric Environment* 35: 1015-1028.
- ²³ Dutkiewicz, Vincent A., Mita Das, and Liaquat Husain. 2000. The relationship between regional SO₂ emissions and downwind aerosol sulfate concentrations in the Northeastern U.S. *Atmospheric Environment* 34: 1821-1832.
- ²⁴ Lynch, James A., Van C. Bowersox, and Jeffrey W. Grimm. 2000b. Changes in sulfate deposition in eastern USA following implementation of Phase I of Title IV of the Clean Air Act Amendments of 1990. *Atmospheric Environment* 34: 1665-1680.
- ²⁵ Shannon, Jack. 1999. Regional trends in wet deposition of sulfate in the United States and SO₂ emissions from 1980 through 1995. *Atmospheric Environment* 33: 807-816.
- ²⁶ Butler, Thomas J., Gene E. Likens, Francoise M. Vermeylen, and Barbara J.B. Stunder. 2003. The relation between NO_x emissions and precipitation NO₃ in the eastern USA. *Atmospheric Environment* 37: 2093-2104.
- ²⁷ Lynch, James A., Van C. Bowersox, and Jeffrey W. Grimm. 2000a. Acid Rain Reduced in Eastern United States. *Environmental Science and Technology* 34: 940-949.
- ²⁸ NADP. 2002. National Atmospheric Deposition Program 2002 Annual Data Summary. NADP, Champaign, IL. <http://nadp.sws.uiuc.edu/isopleths/annualmaps>.
- ²⁹ NAPAP. 1998. NAPAP Biennial Report to Congress: an integrated assessment. National Science and Technology Council, Committee on the Environment and Natural Resources. Silver Spring, MD. 152 pp.
- ³⁰ Driscoll, C.T., G. Lawrence, A. Bulger, T. Butler, C. Cronan, C. Eagar, K.F. Lambert, G.E. Likens, J. Stoddard, and K. Weathers. 2001. Acid deposition in the Northeastern U.S.: Sources and Inputs, Ecosystem Effects, and Management Strategies. *Bioscience* 51:180-198.
- ³¹ NAPAP. 1991. 1990 Integrated Assessment Report. National Acid Precipitation Assessment Program Office of the Director, Washington, DC.
- ³² Clow, D.W. and J.K. Sueker. 2000. Relations between basin characteristics and stream-water chemistry in alpine/subalpine basins in Rocky Mountain National Park, Colorado. *Water Resources Research* 36: 49-61.
- ³³ Murdoch, P.S., D.S. Burns, and G.B. Lawrence. 1998. Relation of Climate change to the Acidification of Surface Waters by Nitrogen Deposition. *Environmental Science and Technology* 32:1642-1647.
- ³⁴ Baron, J. ed. 1992. Biogeochemistry of a subalpine ecosystem: Loch Vale Watershed. Ecological Study Series #90. Springer-Verlag, NY.

- ³⁵ Baedeker, M.J. and L.C. Friedman. 2000. Water, energy, and biogeochemical budgets, a watershed research program. U.S. Geological Survey Fact Sheet 165-99.
- ³⁶ Stoddard, J.L., J.S. Kahl, F.A. Deviney, D.R. DeWalle, C.T. Driscoll, A.T. Herlihy, J.H. Kellogg, P.S. Murdoch, J.R. Webb, and K.E. Webster. 2003. Response of surface water chemistry to the Clean Air Act Amendments of 1990. EPA-620-R-03-001, U.S. Environmental Protection Agency, Washington, DC.
- ³⁷ Murdoch, P.S., J.S. Baron, and T.L. Miller. 2000. Potential effects of climate change on surface-water quality in North America, *Journal of the American Water Resources Association*, v. 36, no. 2, p. 347-366.
- ³⁸ Driscoll, C.T., K.M. Driscoll, K.M. Roy, and M.J. Mitchell. 2003. Chemical Response of Lakes in the Adirondack Region of New York to Declines in Acidic Deposition. *Environmental Science and Technology*. 37, 2036-2042.
- ³⁹ Webb, J.R., F.A. Deviney, Jr., B.J. Cosby, A.J. Bulger, and J.N. Galloway. 2000. Acid deposition and the status of Virginia's wild trout resource: Revisited. POSTER PRESENTATION.
- ⁴⁰ Baron, J.S., H.M. Rueth, A.M. Wolfe, K.R. Nydick, E.J. Allstott, J.T. Minear, and B. Moraska. 2000. Ecosystem responses to nitrogen deposition in the Colorado Front Range. *Ecosystems* 3:352-368.
- ⁴¹ Wolfe, A.P., J.S. Baron, and R.J. Cornett. 2001. Anthropogenic nitrogen deposition induces rapid ecological changes in the Alpine Lakes of the Colorado Front Range (USA) *Journal of Paleolimnology* 25: 1-7.
- ⁴² Williams, M.W. and K.A. Tonnessen. 2000. Critical loads for inorganic nitrogen deposition in the Colorado Front Range, USA. *Ecological Applications* 10: 1648-1665.
- ⁴³ Williams, M.W., J.S. Baron, N. Caine, R. Sommerfeld, and R. Senford, Jr. 1996. Nitrogen saturation in the Rocky Mountains. *Environmental Science and Technology* 30:640-646.
- ⁴⁴ Campbell, D.H., J.S. Baron, K.A. Tonnessen, P.D. Brooks, and P.F. Schuster. 2000. Controls on nitrogen flux in alpine/subalpine watersheds of Colorado. *Water Resources Research* 36: 37-47.
- ⁴⁵ Wigington, P.J. 1999. Episodic acidification: causes, occurrence and significance to aquatic resources. Proceedings of the 1998 PA Acidic Deposition Conference, Vol II. Environmental Resources Research Institute, University Park, PA. NHEERL-COR-2292A.
- ⁴⁶ Bulger, A.J., B.J. Cosby, and J.R. Webb. 2000. Current, Reconstructed Past, and Projected Status of Brook Trout (*Salvelinus Fontinalis*) Streams in Virginia. *Canadian Journal of Fisheries and Aquatic Sciences* 57: 1515-1523.
- ⁴⁷ Heyer, K.E., J.R. Webb, and K.N. Eshleman. 1995. Episodic Acidification of Three Streams in Shenandoah National Park, VA, USA. *Water, Air and Soil Pollution* 85: 523-528.
- ⁴⁸ Eshleman, K.N., T.D. Davies, M. Tranter, and P.J. Wigington. 1995. "A two-component mixing model for predicting regional episodic acidification of surface waters during spring snowmelt periods." *Water Resources Research* 31, 1011-1021.
- ⁴⁹ Webb, J.R., B.J. Cosby, F.A. Deviney, Jr., K.N. Eshleman, and J.N. Galloway. 1995. Change in the Acid-Base Status of an Appalachian Mountain Catchment Following Deforestation by the Gypsy Moth. *Water, Air and Soil Pollution* 85: 535-540.
- ⁵⁰ Winner, W.E. 1994. Mechanistic Analysis of Plant Responses to Air Pollution. *Ecological Applications* 4(4) pp 651-661.
- ⁵¹ Fenn, M.E., M.A. Poth, J.D. Aber, J.S. Baron, B.T. Bormann, D.W. Johnson, A.D. Lemly, S.G. McNulty, D.F. Ryan, and R. Stottlemeyer. 1998. Nitrogen excess in North American ecosystems: predisposing factors, ecosystem responses, and management strategies. *Ecological Applications* 8:706-733.
- ⁵² DeHayes, D.H., P.G. Schaberg, G.J. Hawley, and G.R. Strimbeck. 1999. Acid rain impacts calcium nutrition and forest health: alteration of membrane-associated calcium leads to membrane destabilization and foliar injury in red spruce. *Bioscience*. 49:789-800.

- ⁵³ Likens, G.E., C.T. Driscoll, and D.C. Buso. 1996. Long-term effects of acid rain: Responses and recovery of a forest ecosystem. *Science* 272:244-246.
- ⁵⁴ Bailey, S.W., J.W. Hornbeck, C.T. Driscoll, and H.E. Gaudett. 1996. Calcium inputs and transport in a base poor forest ecosystem as interpreted by Sr isotopes. *Water Resources Research* 32:707-719.
- ⁵⁵ Lawrence, G.B., M.B. David, G.M. Lovett, P.S. Murdoch, D.A. Burns, J.L. Stoddard, B.P. Baldigo, J.H. Porter, and A.W. Thompson. 1999. Soil calcium status and the response of stream chemistry to changing acidic deposition rates in the Catskill Mountains of New York. *Ecological Applications* 9:1059-1072.
- ⁵⁶ Adams, M.B. 1999. Acidic deposition and sustainable forest management in the central Appalachians, USA. *Forest Ecology and Management* 12:17-28.
- ⁵⁷ Knoepp, J.D. and W.T. Swank. 1994. Long-term soil chemistry changes in aggrading forest ecosystems. *Soil Science Society of America Journal* 58:325-331.
- ⁵⁸ Markewitz, D., D.D. Richter, H.L. Allen, and J.B. Urrego. 1998. Three decades of observed soil acidification in the Calhoun Experimental Forest: Has acid rain made a difference? *Soil Science Society of America Journal* 62:1428-1439.
- ⁵⁹ Trettin, C.A., D.W. Johnson, and D.E. Todd, Jr. 1999. Forest nutrient and carbon pools: a 21-year assessment. *Soil Science Society of America Journal* 63: 1436-1448.
- ⁶⁰ Watmough, S.A., and P. Dillon. 2003. Calcium losses from a forested catchment in south-central Ontario, Canada. *Environmental Science and Technology* 37:3085-3089.
- ⁶¹ Drohan, J.R. and W.E. Sharpe. 1997. Long-term changes in forest soil acidity in Pennsylvania, USA. *Water, Air and Soil Pollution* 95:299-311.
- ⁶² Yanai, R.D., T.G. Siccama, M.A. Arthur, C.A. Federer, and A.J. Friedland. 1999. Accumulation and depletion of base cations in forest floors in the Northeastern United States. *Ecology* 80:2774-2787.
- ⁶³ Hamburg, S.P., R.D. Yanai, M.A. Arthur, J.D. Blum, and T.G. Siccama. 2003. Biotic Control of Calcium Cycling in Northern Hardwood Forests: Acid Rain and Aging Forests. *Ecosystems* 6, 399-406.
- ⁶⁴ Johnson, D.W. and D.E. Todd. 1998. The effects of harvesting on long-term changes in nutrient pools in a mixed oak forest. *Soil Science Society of America Journal* 62: 1725-1735.
- ⁶⁵ Huntington, T.G. 2000. The potential for calcium depletion in forest ecosystems of Southeastern United States: review and analysis. *Global Biogeochemical Cycles* 14, 623-638.
- ⁶⁶ Joensson, U., U. Rosengren, G. Thelin, and B. Nihlgård. 2003. Acidification-induced chemical changes in coniferous forest soils in southern Sweden 1988-1999 *Environmental Pollution* 123:75-83.
- ⁶⁷ McLaughlin, S.B. and R. Wimmer. 1999. Tansley Review No. 104, Calcium physiology and terrestrial ecosystem processes. *New Phytologist* 142:373-417.
- ⁶⁸ Schaberg, P.G., D.H. DeHayes, and G.J. Hawley. 2001. Anthropogenic calcium depletion: a unique threat to forest ecosystem health? *Ecosystem Health* 7:214-228.
- ⁶⁹ Huntington, T.G., R.P. Hooper, C.E. Johnson, B.T. Aulenbach, R. Cappellato, and A.E. Blum. 2000. Calcium depletion in a Southeastern United States forest ecosystem. *Soil Science Society of America Journal* 64:1845-1858.
- ⁷⁰ Turner, R.S., R.B. Cook, H. Van Miegroet, D.W. Johnson, J.W. Elwood, B.O.P., S.E. Lindberg, and G.M. Hornberger. 1990. Watershed and lake processes affecting surface water acid-base chemistry, in *Acid Deposition: State of Science and Technology*, Rep. 10, pp. 1-167, National Acid Precipitation Assessment Program, Washington, DC, Nov. 1990.
- ⁷¹ Johnson, D.W. and S.E. Lindberg. 1992. *Atmospheric Deposition and Forest Nutrient Cycling*; Springer-Verlag: New York.

- ⁷² Dijkstra, F.A., N. VanBreemen, A.G. Jongman, G.R. Davies, and G.E. Likens. 2003. Calcium weathering in forested soils and the effect of different tree species. *Biogeochemistry* 62, 253-275.
- ⁷³ Long, R.P., S.B. Horsley, and P.R. Lilja. 1997. Impact of forest liming on growth and crown vigor of sugar maple and associated hardwoods. *Canadian Journal of Forest Research* 27:1560-1573.
- ⁷⁴ Horsley, S.B., R.P. Long, S.W. Bailey, R.A. Hallett, and T.J. Hall. 2000. Factors associated with the decline disease of sugar maple on the Allegheny Plateau. *Canadian Journal of Forest Research* 30:1365-1378.
- ⁷⁵ Moore, J.D., C. Camire, and R. Ouimet. 2000. Effects of liming on the nutrition, vigour, and growth of sugar maple at the Lake Clair Watershed, Quebec, Canada. *Canadian Journal of Forest Research* 30:725-732.
- ⁷⁶ Watmough, S.A. 2002. A Dendrochemical Survey of Sugar Maple (*Acer saccharum* Marsh) in South-Central Ontario, Canada, *Water, Air and Soil Pollution*, 136:165-187.
- ⁷⁷ Drohan, P., S.L. Stout, and G. Petersen. 2002. Sugar maple (*Acer saccharum* Marsh) decline during 1979-1989 in northern Pennsylvania. *Forest Ecology and Management* 170:1-17.
- ⁷⁸ Fenn, M.E., R. Haeuber, G.S. Tonnesen, J.S. Baron, S. Grossman-Clarke, D. Hope, D.A. Jaffe, S. Copeland, L. Geiser, H.M. Rueth, and J.O. Sickman. 2003c. Nitrogen emissions, deposition, and monitoring in the Western United States. *Bioscience* 53: 391-403.
- ⁷⁹ Aber, J., K. Nadelhoffer, P. Steudler, and J. Melillo. 1989. Nitrogen saturation in northern forest ecosystems. *Bioscience* 39:378-386.
- ⁸⁰ Fenn, M.E., M.A. Poth, S.L. Schilling, and D.B. Grainger. 2000. Throughfall and fog deposition of nitrogen and sulfur at an N-limited and N-saturated site in the San Bernardino Mountains, southern California. *Canadian Journal of Forest Research* 30:1476-1488.
- ⁸¹ Fenn, M.E., M.A. Poth, A. Bytnerowicz, J.O. Sickman, and B.K. Takemoto. 2003b. Effects of ozone, nitrogen deposition, and other stressors on montane ecosystems in the Sierra Nevada. pp. 111-155 In A. Bytnerowicz, M.J. Arbaugh, and R. Alonso (eds.), *Developments in Environmental Science, volume 2: Ozone Air Pollution in the Sierra Nevada: Distribution and Effects on Forests*. Elsevier. Amsterdam.
- ⁸² Howarth, R.W., D.M. Anderson, T.M. Church, H. Greening, C.S. Hopkinson, W.C. Huber, N. Marcus, R.J. Naiman, K. Segerson, A.N. Sharpley, and W.J. Wiseman. 2000. *Clean Coastal Waters: understanding and reducing the effects of nutrient pollution*. National Academy of Sciences, Washington, DC.
- ⁸³ Bricker, S.B., C.G. Clements, D.E. Pirhalla, S.P. Orlando, and D.R.G. Farrow. 1999. *National Eutrophication Assessment: effects of nutrient enrichment in the nation's estuaries*. NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Silver Spring, MD.
- ⁸⁴ Davidson, C.I., W. Tang, S. Finger, V. Etyemezian, M.F. Striegel, and S.I. Sherwood. 2002. "Soiling Patterns on a Tall Limestone Building: Changes Over Sixty Years," *Environmental Science and Technology*, Vol. 34, pp. 560-565.
- ⁸⁵ Etyemezian, V., C.I. Davidson, M. Zufall, W. Dai, S. Finger, and M. Striegel. 2000. "Impingement of Rain Drops on a Tall Building," *Atmospheric Environment*, Vol. 34, pp. 2399-2412.
- ⁸⁶ Tang, W., C.I. Davidson, S. Finger, and M.F. Striegel. 2002. "Wind-driven rain on a tall limestone building: Washoff of soiling caused by pollutant deposition" in *Atmospheric deposition and its impact on ecosystems: Proceedings, International Symposium on Atmospheric Deposition and Impacts on Ecosystems*. R. Van Grieken and Y. Shevah, Eds. (Antwerp, Belgium: University of Antwerp Press). 170 pg.
- ⁸⁷ Reddy, M.M., S.I. Sherwood, and B.R. Doe. 1986. Limestone and marble dissolution by acid rain: an onsite weathering experiment. In *"Materials Degradation Caused by Acid Rain."* (R. Baboian, Ed.) American Chemistry Society Symposium Series 318, pp. 226-238.

- ⁸⁸ Charola, E.A. 2001. Acidic deposition on stone. *U.S./ICOMOS Scientific Journal III*(1):19-58.
- ⁸⁹ Zinn, M., T. Perry, M. Breuker, and R. Mitchell. 2000. "Deterioration of historic limestone materials by biofilms in a polluted environment," In Proc. Annual Meeting *American Society of Microbiology Q*, 156.
- ⁹⁰ Holland, David M., Peter P. Principe, and Joseph E. Sickles, II. 1999. Trends in atmospheric sulfur and nitrogen species in the Eastern United States for 1989-1995. *Atmospheric Environment* 33: 37-49.
- ⁹¹ Brook, J.R., F. Di-giovanni, S. Cakmak, and T.P. Meyers. 1997. Estimation of dry deposition velocity using inferential models and site-specific meteorology - uncertainty due to siting of meteorological towers. *Atmospheric Environment* 31: 3911-3919.
- ⁹² Clarke, J.F., E.S. Edgerton, and B.E. Martin. 1997. Dry deposition calculations for the Clean Air Status and Trends Network. *Atmospheric Environment* 31: 3667-3668.
- ⁹³ Finkelstein, P.L., T. Ellestad, J.F. Clarke, T.P. Meyers, D.B. Schwede, E.O. Hebert, and J.A. Neal. 2000. Ozone and sulfur dioxide dry deposition to forests: observations and model evaluation. *Journal of Geophysical Research* 105: 15365-15377.
- ⁹⁴ Sickles, J.E., II, L.L. Hodson, and L.M. Vorburger. 1999. Evaluation of filter pack for long-duration sampling of ambient air. *Atmospheric Environment* 33: 2187-2202.
- ⁹⁵ Draaijers, G.P.J., J.W. Erisman, T. Spranger, and G.P. Wyers. 1996. The application of throughfall measurements for atmospheric deposition monitoring. *Atmospheric Environment* 30: 3349-3361.
- ⁹⁶ Lovett, G.M. 1994. Atmospheric deposition of nutrients and pollutants in North America: An ecological perspective. *Ecological Applications* 4: 629-650.
- ⁹⁷ Holland, D.M. and A. Sirois. 2002. Estimation of Temporal Trends in Wet Deposition: A Brief Overview. Acid Rain Modeling. Encyclopedia of Environmetrics, Vol 1 (eds. A. H. El-Shaarawi and W. Piegorsch). John Wiley & Sons, Ltd, Chichester, pp 14-25.
- ⁹⁸ Lawrence, G.B., D.A. Burns, B.P. Baldigo, P.S. Murdoch, and G.M. Lovett. 2001. Controls of stream chemistry and fish populations in the Neversink watershed, Catskill Mountains, New York, U.S. Geological Survey Water-Resources Investigations Report 00-4040, 16 p.
- ⁹⁹ Driscoll, C.T., K.M. Postek, D. Mateti, K. Sequeira, J.D. Aber, W.J. Kretser, M.J. Mitchell, and D.J. Raynal. 1998. The Response of Lake Water in the Adirondack Region of New York State to Changes in Acid Deposition. *Environmental Science and Policy* 1: 185-198.
- ¹⁰⁰ Norton, S.A., J.S. Kahl, I.J. Fernandez, T.A. Haines, L.E. Rustad, S. Nodvin, J.P. Scofield, T. Strickland, H. Erickson, P. Wiggington, and J. Lee. 1999. The Bear Brook Watershed, Maine, (BBWP) USA. *Environmental Monitoring and Assessment* 55:7-51.
- ¹⁰¹ Kahl, J.S., S.A. Norton, I.J. Fernandez, K.J. Nadelhoffer, C.T. Driscoll, and J.D. Aber. 1993. Experimental inducement of nitrogen saturation at the watershed scale. *Environmental Science and Technology* 27:565-568.
- ¹⁰² Kahl, J.S., S.A. Norton, I.J. Fernandez, L. Rustad, and M. Handley. 1999. Nitrogen and sulfur input-output budgets in the experimental and reference watersheds, Bear Brook Watershed, Maine (BBWM). *Environmental Monitoring and Assessment* 55:113-131.
- ¹⁰³ Herlihy, A.T., P.R. Kaufman, M.R. Church, P.J. Wiggington, Jr., J.R. Webb, and M.J. Sale. 1993. The Effects of Acidic Deposition on Streams in the Appalachian Mountain and Piedmont Region of the Mid-Atlantic United States. *Water Resources Research*, 29(8) pp 2687-2703.
- ¹⁰⁴ Liegel, L., D. Cassell, D. Stevens, P. Shaffer, and R. Church. 1991. Regional Characteristics of Land Use in Northeast and Southern Blue Ridge Province USA Associations with Acid Rain Effects on Surface-Water Chemistry. *Environmental Management*, Volume: 15, Number: 2, Page: 269-280.

- ¹⁰⁵ Webb, J.R., F.A. Deviney, J.N. Galloway, C.A. Rinehart, P.A. Thompson, and S. Wilson. 1994. The Acid-Base Status of Native Brook Trout Streams in the Mountains of Virginia: A Regional Assessment Based on the Virginia Trout Stream Sensitivity Study. Report to the Virginia Department of Game and Inland Fisheries, Charlottesville.
- ¹⁰⁶ Van Sickle, J. and M.R. Church. 1995. Methods for Estimating the Relative Effects of Sulfur and Nitrogen Deposition on Surface Water Chemistry. EPA-600-R-95-172. U.S. Environmental Protection Agency, Washington, DC.
- ¹⁰⁷ Southern Appalachian Man in the Biosphere (SAMAB). 1996. The Southern Appalachian Assessment Aquatic Resources Technical Report. Atlanta: U.S. Department of Agriculture, Forest Service, Southern Region. Chapter 2. 15-64.
- ¹⁰⁸ Herlihy, A.T., P.R. Kaufman, J.L. Stoddard, K.N. Eshleman, and A.J. Bulger. 1996. Effects of Acidic Deposition on Aquatic Resources in the Southern Appalachians with a Special Focus on Class I Wilderness Areas. Prepared for the Southern Appalachian Mountains Initiative (SAMI).
- ¹⁰⁹ Sickman, J.O. and J.M. Melack. 1989. Characterization of year-round sensitivity of California's montane lakes to acid deposition. Final Report. Contrib. A5-203-32. California Air Resources Board, Sacramento, CA.
- ¹¹⁰ Melack, J.M., J.O. Sickman, F.V. Setaro, and D. Engle. 1993. Long-term studies of lakes and watersheds in the Sierra Nevada, patterns and processes of surface-water acidification. Final Report, Contract No. A932-060, to California Air Resources Board. Marine Science Institute, Univ. of California, Santa Barbara, CA.
- ¹¹¹ Melack, J.M., J.O. Sickman, and A. Leydecker. 1998. Comparative analyses of high-altitude lakes and catchments in the Sierra Nevada: susceptibility to acidification. Final Report prepared for the California Air Resources Board, Contract A032-188. Marine Science Institute and Institute for Computational Earth System Science, University of California, Santa Barbara, CA.
- ¹¹² Fenn, M.E. and M.A. Poth. 1999a. Temporal and Spatial Trends in Streamwater Nitrate Concentrations in the San Bernardino Mountains, southern California. *Journal of Environmental Quality* 28: 822-836.
- ¹¹³ Riggan, P.J., R.N. Lockwood, and E.N. Lopez. 1985. Deposition and processing of airborne nitrogen pollutants in Mediterranean-type ecosystems of southern California. *Environmental Science and Technology* 19: 781-789.
- ¹¹⁴ Riggan, P.J., R.N. Lockwood, P.M. Jacks, C.G. Colver, F. Weirich, L.F. DeBano, and J.A. Brass. 1994. Effects of fire severity on nitrate mobilization in watersheds subject to chronic atmospheric deposition. *Environmental Science and Technology* 28:369-375.
- ¹¹⁵ Lawrence, G.W., M.B. David, S.W. Bailey, and W.C. Shortle. 1997. Assessment of calcium status in soils of red spruce forests in the Northeastern United States. *Biogeochemistry* 38:19-39.
- ¹¹⁶ Shortle, W.C. and K.T. Smith. 1988. Aluminum-induced calcium deficiency syndrome in declining red spruce trees. *Science* 240:1017-1018.
- ¹¹⁷ Lawrence, G.B., M.B. David, and W.S. Shortle. 1995. A new mechanism for calcium loss in forest floor soils. *NH. Nature* 378:162-165.
- ¹¹⁸ Kennedy, M.J., L.O. Hedin, and L.A. Derry. 2002. Decoupling of unpolluted temperate forests from rock nutrient sources revealed by natural ⁸⁷Sr/⁸⁶Sr and ⁸⁴Sr tracer addition. *Proc. National Academy of Sciences* 99:9639-9644.
- ¹¹⁹ McLaughlin, S.B. and R. Wimmer. 1999. Tansley Review No. 104 Calcium physiology and its role in terrestrial ecosystem processes. *New Phytologist* 142:373-417.

- ¹²⁰ Smith, K.T. and W.C. Shortle. 2001. Conservation of element concentration in xylem sap of red spruce. *Trees* 15:148-153.
- ¹²¹ Shortle, W.C., K.T. Smith, R. Minocha, G.B. Lawrence, and M.B. David. 1997. Acidic deposition, cation mobilization, and biochemical indicators of stress in healthy red spruce. *Journal of Environmental Quality* 26:871-876.
- ¹²² Schaberg, P.G., D.H. DeHayes, G.J. Hawley, G.R. Strimbeck, J.R. Cumming, P.F. Murakami, and C.H. Borer. 2000. Acid mist, soil calcium and aluminum alter the mineral nutrition and physiology of red spruce. *Tree Physiology* 20:73-85.
- ¹²³ Mitchell, M.J., C.T. Driscoll, J.S. Kahl, G.E. Likens, P.S. Murdoch, and L.H. Pardo. 1996. Climate control on nitrate loss from forested watersheds in the Northeast United States. *Environmental Science and Technology* 30: 2609-2612.
- ¹²⁴ Mitchell, M.J., M.B. David, I.J. Fernandez, R.D. Fuller, K. Nadelhoffer, L.E. Rustad, and A.C. Stam. 1994. Response of buried mineral soil bags to experimental acidification of forest ecosystem. *Soil Science Society of America Journal* 58:556-563.
- ¹²⁵ Norton, S.A., J.S. Kahl, I.J. Fernandez, L.E. Rustad, J.P. Schofield, and T.A. Haines. 1994. Response of the West Bear Brook Watershed, Maine, USA, to the addition of (NH₄)₂SO₄: 3-year results. *Forest and Ecology Management* 68:61-73.
- ¹²⁶ Rustad, L.E., I.J. Fernandez, M.B. David, M.J. Mitchell, K.J. Nadelhoffer, and R.D. Fuller. 1996. Experimental soil acidification and recovery at the Bear Brook Watershed in Maine. *Soil Science of America Journal* 60: 1933-1943.
- ¹²⁷ MacDonald, N.W., A.J. Burton, H.O. Liechty, J.A. Whitter, K.S. Pregitzer, G.D. Mroz, and D.D. Richter. 1992. Ion leaching in forest ecosystems along a Great Lakes air pollution gradient. *Journal of Environmental Quality* 21:614-623.
- ¹²⁸ Adams, M.B., T.R. Angradi, and J.N. Kochenderfer. 1997. Stream water and soil solution responses to 5 years of nitrogen and sulfur additions at the Fernow Experimental Forest, West Virginia. *Forest Ecology and Management* 95: 79-91.
- ¹²⁹ Adams, M.B., J.A. Burger, A.B. Jenkins, and L. Zelazny. 2000. Impact of harvesting and atmospheric pollution on nutrient depletion of eastern U.S. hardwood forests. *Forest Ecology and Management* 138: 301-319.
- ¹³⁰ Grulke, N.E., C.P. Anderson, M.E. Fenn, and P.R. Miller. 1998. Ozone and nitrogen deposition reduces root biomass of ponderosa pine in the San Bernardino Mountains. *California Environmental Pollution* 103:63-73.
- ¹³¹ Grulke, N.E., C.P. Andersen, and W.E. Hogsett. 2001. Seasonal changes in above- and belowground carbohydrate concentrations of ponderosa pine along a pollution gradient. *Tree Physiology* 21:173-181.
- ¹³² Fenn, M.E. and M.A. Poth. 1999b. Nitrogen deposition and cycling in Mediterranean forests: The new paradigm of nitrogen excess. pp. 288-314 In P.R. Miller and J.R. McBride (eds.), *Oxidant Air Pollution Impacts on the Montane Forests of Southern California: A Case Study of the San Bernardino Mountains, Ecological Studies* 134. Springer-Verlag, New York, NY.
- ¹³³ Fenn, Mark E., Jill S. Baron, Edith B. Allen, Heather M. Rueth, Koren R. Nydick, Linda Geiser, William D. Bowman, James O. Sickman, Thomas Meixner, Dale W. Johnson, and Peter Neitlich. 2003a. Ecological Effects of Nitrogen Deposition in the Western United States. *Bioscience* 53 : 404-420.
- ¹³⁴ Padgett, P.E., E.B. Allen, A. Bytnerowicz, and R.A. Minnich. 1999. Changes in soil inorganic nitrogen as related to atmospheric nitrogenous pollutants in southern California. *Atmospheric Environment* 33:769-781.

- ¹³⁵ Allen, E.B., P.E. Padgett, A. Bytnerowicz, and R. Minnich. 1998. Nitrogen deposition effects on coastal sage vegetation of southern California. pp. 131-139 In Proceedings of the International Symposium on Air Pollution and Climate Change Effects on Forest Ecosystems, 5-9 Feb. 1996. Riverside, CA. Gen. Tech. Rep. PSW-GTR-166. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Dept. of Agriculture.
- ¹³⁶ Bytnerowicz, A., P. Padgett, K. Percy, M. Krywult, G. Riechers, and J. Hom. 1999. Direct effects of nitric acid on forest trees. pp. 270-287 In P.R. Miller and J.R. McBride (eds.), Oxidant Air Pollution Impacts on the Montane Forests of Southern California: A Case Study of the San Bernardino Mountains, *Ecological Studies* 134. Springer-Verlag, New York, NY.
- ¹³⁷ Valigura, R.A., R.B. Alexander, M.S. Castro, T.P. Meyers, H.W. Paerl, P.E. Stacy, and R.E. Turner. 2001. Nitrogen Loading in Coastal Water Bodies: an atmospheric perspective. American Geophysical Union, Washington, DC.
- ¹³⁸ Howarth. 1998. An assessment of human influences on fluxes of nitrogen from the terrestrial landscape to the estuaries and continental shelves of the North Atlantic Ocean. *Nutrient Cycling in Agroecosystems* 52(2/3): 213-223.
- ¹³⁹ Aggelakopoulou, E., P. Charles, M.E. Acerra, A.I. Garcia, R.J. Flatt, and G.W. Scherer. 2001. Rheology optimization of particle modified consolidants. Materials Issues in Art & Archeology VI, Materials Research Society.
- ¹⁴⁰ Escalante, M.R., J. Valenza, and G.W. Scherer. 2000. Compatible consolidants from particle-modified gels. In Vasco Vassina, ed, 9th International Congress on Deterioration and Conservation of Stone 2, ed. Vasco Vassina, Vol 2 : (Amsterdam, Netherlands: Elsevier Science) 459-65.
- ¹⁴¹ Bierwagen, Gordon, T. Shedlosky, and K. Stanek. 2003. Developing and Testing a New Generation of Protective Coatings for Outdoor Bronze Sculpture. *Progress in Organic Coatings* 48 (2003) 289-296.
- ¹⁴² U.S. EPA. 1996. Air Quality Criteria for Particulate Matter. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA-600-P-95-001aF.
- ¹⁴³ Samet, J.M., S.L. Zeger, F. Dominici, F. Curriero, I. Coursac, D.W. Dockery, J. Schwartz, and A. Zanobetti. 2000. The National Morbidity, Mortality and Air Pollution Study: Part II: Morbidity, Mortality and Air Pollution in the United States. Research Report No. 94, Part II. Health Effects Institute, Cambridge MA, June 2000.
- ¹⁴⁴ Krewski D., R.T. Burnett, M.S. Goldbert, K. Hoover, J. Siemiatycki, M. Jerrett, M. Abrahamowicz, and W.H. White. 2000. Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality. Special Report to the Health Effects Institute, Cambridge, MA.
- ¹⁴⁵ Health Canada. 1999. National ambient air quality objectives for particulate matter; Part 1: science assessment document. Health Canada, Bureau of Chemical Hazards, Environmental Health Directorate, Tunney's Pasture, Ottawa, Ontario, K1A 0L2.
- ¹⁴⁶ World Health Organization. 2000. Air Quality Guidelines for Europe, Second Edition. World Health Organization Regional Office for Europe, Scherfigzvej 8, DK-2100 Copenhagen y, Denmark. WHO Regional Publications, European Series, No. 91.
- ¹⁴⁷ Donaldson, K., V. Stone, A. Seaton, and W. MacNee. 2001. Ambient particle inhalation and the cardiovascular system: potential mechanisms. *Environmental Health Perspectives* 109(Supplement 4):523-527.
- ¹⁴⁸ Salvi, S. and S.T. Holgate. 1999. Mechanisms of particulate matter toxicity. *Clinical and Experimental Allergy* 29(9):1187-1194.
- ¹⁴⁹ Berge, E. and H. A. Kakobsen. 1998. A regional scale multi-layer model for the calculation of long-term transport and deposition of air pollution in Europe. *Tellus*, 50, 205-223.

- ¹⁵⁰ Carmichael, G. R., L. K. Peters, and R. D. Saylor. 1991. The STEM-II regional acid deposition and photochemical oxidant model-1. An overview of model development and application. *Atmos. Environ.*, 25A, 2077-2090.
- ¹⁵¹ West, J.J., A.S. Ansari, and S.N. Pandis. 1999. Marginal PM_{2.5}: Nonlinear Aerosol Mass Response to Sulfate Reductions in the Eastern United States. *Journal of Air & Waste Management Association* 49: 1415-1424.
- ¹⁵² Cosby, B.J., G.M. Hornberger, J.N. Galloway, and R.F. Wright. 1985a. Modeling the effect of acid deposition: assessment of a lumped parameter model of soil water and streamwater chemistry. *Water Resources Research* 21: 51-63.
- ¹⁵³ Cosby, B.J., R.F. Wright, G.M. Hornberger, and J.N. Galloway. 1985b. Modeling the effect of acid deposition: estimation of a long term water quality responses in a small forested catchment. *Water Resources Research* 21: 1591-1603.
- ¹⁵⁴ Cosby, B.J., G.M. Hornberger, J.N. Galloway, and R.F. Wright. 1985c. Timescales of catchment acidification. *Environmental Science and Technology*. 19: 1144-1149.
- ¹⁵⁵ Binkowski, F.S. and U. Shankar. 1995. The regional particulate model. 1. Model description and preliminary results. *Journal of Geophysical Research* 100:26191-26209.
- ¹⁵⁶ Ching, J., F.S. Binkowski, and J.E. Pleim. 1996. Preliminary results: Modeling fine particulate mass for the Eastern United States using the EPA Regional Particulate Model. In: *Air Pollution Modeling and Its Application XI*, S-E. Gryning and F. Schiermeier (Eds.), Plenum Press, NY, pp. 135-144.
- ¹⁵⁷ Bay Journal. 1995. How the regional air pollution model works. In *Alliance for the Chesapeake Bay Journal*, 5(1).
- ¹⁵⁸ Moran, M.D. 1997. Evaluation of the impact of North American SO₂ emission control legislation on the attainment of SO₄ critical loads in eastern Canada. Paper No. 97-TA28.01, presented at the 90th Annual Meeting and Exhibition of the Air and Waste Management Association, Toronto, Ontario.
- ¹⁵⁹ Reynolds, S.D., P.M. Roth, and J.H. Seinfeld. 1973. Mathematical modeling of photochemical air pollution. I. Formulation of model. *Atmospheric Environment* 7: 1033-1061.
- ¹⁶⁰ McRae, G.J., W.R. Goodin, and J.H. Seinfeld. 1982b. Development of a second generation mathematical model for urban air pollution. I. Model formulation, *Atmospheric Environment* 16: 679-696.
- ¹⁶¹ Harley, R.A., A.G. Russell, G.J. McRae, G.R. Cass, and J.H. Seinfeld. 1993. Photochemical Modeling of the Southern California Air Quality Study. *Environmental Science and Technology* 27: 378-388.
- ¹⁶² Gbondo-Tugbawa, S.S., C.T. Driscoll, J.D. Aber, and G.E. Likens. 2001. Evaluation of an integrated biogeochemical model (PnET-BGC) at a northern hardwood forest ecosystem. *Water Resources Research* 37:1057-1070.
- ¹⁶³ U.S. EPA. 2004. Air Quality Criteria for Particulate Matter (October 2004), Volumes I & II. U.S. Environmental Protection Agency, Office of Research and Development, Washington DC. EPA/600/P-99/002aF and EPA/600/P-99/002bF.
- ¹⁶⁴ U.S. EPA. 1999. The Benefits and Costs of the Clean Air Act 1990-2010, Report to Congress. EPA-410-R-99-001. Washington, DC.
- ¹⁶⁵ Bulger, A.J., B.J. Cosby, and J.R. Webb. 1998. Acid Rain: Current and projected status of coldwater fish communities in the Southeastern U.S. in the context of continued acid deposition. Trout Unlimited, Arlington Virginia. 28 p.
- ¹⁶⁶ U.S. EPA. 1995a. Human Health Benefits from Sulfate Reductions under Title IV of the 1990 Clean Air Act Amendments, November 1995, EPA 430-R-95-010.

- ¹⁶⁷ Burtraw, Dallas. 1998. Cost Savings, Market Performance, and Economic Benefits of the U.S. Acid Rain Program. *Resources for the Future*. 98-28 REV.
- ¹⁶⁸ Ostro, Bart D., Lauraine G. Chestnut, David M. Mills, and Ann M. Watkins. 1999. Estimating the Effects of Air Pollutants on the Population: Human Health Benefits of Sulfate Aerosol Reductions under Title IV of the 1990 Clean Air Act Amendments. *Air Pollution and Health*, edited by Stephen T. Holgate, et al. Academic Press, Chapter 39, 899-915.
- ¹⁶⁹ Watkins, Ann Miller. 2001. Outdoor Pollution: Acid Rain. In Luanne Kemp Williams & Ricky L. Langley, eds, *Environmental Health Secrets*.
- ¹⁷⁰ Burtraw, Dallas and Karen Palmer. 2003. "The Paparazzi Take a Look at a Living Legend: The SO₂ Capand-Trade Program for Power Plants in the United States" April 2003, RFF Discussion Paper 03-15.
- ¹⁷¹ Office of Management & Budget. 2003. Informing Regulatory Decision: 2003 Report to Congress on the Costs and Benefits of federal Regulations and Unfunded Mandates on State, Local, and Tribal Entities, pp. 88 and 89. (www.whitehouse.gov/omb/inforeg/2003_cost-ben_final_rpt.pdf).
- ¹⁷² Gilmour, C.C. and E.A. Henry. 1991. Mercury methylation in aquatic system affected by acid deposition. *Environmental Pollution* 71: 131-149.
- ¹⁷³ Driscoll, C.T., K.M. Driscoll, M.J. Mitchell, and D.J. Raynal. 2003. Effects of acid deposition on forest and aquatic ecosystems in New York State. *Environmental Pollution* 123: 327-336.
- ¹⁷⁴ NAPAP. 1990b. Acid Deposition: State of Science and Technology, Volume II Aquatic processes and Effects. National Acid Precipitation Assessment Program Office of the Director, Washington, DC.
- ¹⁷⁵ U.S. EPA. 1995b. Acid Deposition Standard Feasibility Study Report to Congress. Washington, DC. EPA 430-R-95-001a.
- ¹⁷⁶ Ecological Society of America. 1997. Atmospheric Nitrogen Deposition to Coastal Watersheds. (Washington, DC: Ecological Society of America, www.esa.org/sbi/sbi_publications/sbindep1.htm).
- ¹⁷⁷ Ecological Society of America. 1999. Acid Deposition: The Ecological Response. Washington, DC: Ecological Society of America, (www.esa.org/sbi/sbi_publications/aciddep.htm).
- ¹⁷⁸ Southern Appalachians Mountains Initiative (SAMI). 2002. Southern Appalachians Mountain Initiative Final Report.
- ¹⁷⁹ U.S. EPA. 2003b. Technical Support Document for the Clear Skies Act 2003 Air Quality Modeling Analyses. U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Emissions Analysis and Monitoring Division Research Triangle Park.

To contact the NAPAP organization or to request copies of this report,
contact National Acid Precipitation Assessment Program

NOAA, MailCode R/WA
Room 11216
1315 East-West Highway
Silver Spring, MD 20910

Telephone: (301) 713-0460 x202
Fax: (301) 713-3515

e-mail: napap@noaa.gov

Electronic information on NAPAP, as well as an electronic version of this report,
are available at www.napap.noaa.gov/reports

